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Journal of Experimental Psychology

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THE NATURE OF ACOUSTIC RESPONSE: THE RELATION BETWEEN SOUND FREQUENCY AND FREQUENCY OF IMPULSES IN THE AUDITORY NERVE [1]

BY ERNEST GLEN WEVER AND CHARLES W. BRAY

Princeton University

Theories of audition consist essentially of speculations concerning the processes intervening between the application of sounds to the ear and the phenomena of hearing. The theories are concerned with the processes occurring in the peripheral system—in the cochlea and in the acoustic nerve—as correlates of the frequencies and intensities of vibrations perceptible as sound. The evidence at present available goes little farther than a fairly precise understanding of the anatomy of the ear and a knowledge of the phenomena of hearing, and since this evidence is equivocal we have many theories of audition and no manner of deciding among them. Direct exploration of the peripheral processes is therefore needed, and the present investigation arose from the suggestion that a final solution of the problem of audition may be found by an

[1] From the Psychological Laboratory. This is the first of a series of experiments on this subject. An advance notice of these experiments appeared in *Science*, 1930, **71**, 215, and a preliminary report was read before the National Academy of Sciences on April 28, 1930; see *Proc. Nat. Acad. Sci.*, 1930, **16**, 344–350.

Many, by advice, encouragement, and criticisms, have contributed to the progress of this investigation. We are happy to acknowledge first of all the kind coöperation of Professor H. S. Langfeld, who as Director of the Laboratory has aided us in many ways, particularly in placing at our disposal the extensive physical resources required by the experiments. We wish also to thank Professor E. N. Harvey, of the Department of Biology, who by advice and suggestions has helped us at some difficult points, and Mr. G. P. Horton, who has kindly assisted in many of the experiments.

examination of the action currents set up in the auditory nerve during stimulation of the ear by sound.[1]

The cat was selected as a suitable animal for this investigation. It stands fairly high in the animal scale, and we have casual and experimental evidence indicating its hearing to be comparable to that of man.[2] And also, recent experiments have given us a higher degree of acquaintanceship with nerve responses in general in this animal than in any other mammal.

Procedure

The procedure of the experiment consisted in placing electrodes on the exposed auditory nerve, and leading off the nerve action currents through an amplifying system to a detecting apparatus.

The operative technique leading to the exposure of the nerve is of course a primary feature of the investigation, and we shall therefore describe in detail the technique which we have developed.

Operative technique.—Under deep ether anesthesia the throat is opened and a tracheal cannula inserted. At the same time the carotid arteries may be tied; we have done this in most cases, but it is not necessary.

The skull is then laid bare, and opened in the parietal region of one side. The opening is enlarged sufficiently to permit decerebration and the subsequent removal of cerebral tissue.

The decerebration is performed through a slit in the dura, and consists in a careful separation of the cerebral tissues from the brain stem at the level of the tentorium. The separation is made with a blunt probe, care being taken to keep within the dura, and thus to leave the arterial circle uninjured. With this sort of handling, there is very little bleeding, and the vertebral arteries do not need to be held. Finally the

[1] *Cf.* E. G. Boring, Auditory theory with special reference to intensity, volume, and localization, *Amer. J. Psychol.*, 1926, **37**, pp. 181 *f.* Some of the theoretical questions raised in our investigation are discussed in an article on Present possibilities for auditory theory, *Psychol. Rev.*, 1930, **37**, 365 *ff.*

[2] E. G. Wever, The upper limit of hearing in the cat, *J. Comp. Psychol.*, 1930, **10**, 221–233.

cerebral hemispheres are removed wholly or in part, to prevent the tissue falling into the field of subsequent operation. The anesthetic is of course stopped after decerebration.

The skull opening is then carried backward across the tentorium and over the cerebellum to the lambdoidal ridge. It is enlarged sufficiently to permit the removal of considerable cerebellar tissue, and finally carried laterally up to the petrous bone. With fine forceps the dura and other delicate tissues intervening between the skull opening and the auditory nerve are removed, and the nerve thus exposed as it leaves the internal auditory meatus and enters the medulla.

The size and length of nerve exposed by this method varies greatly in different animals. The diameter at the internal meatus varies between 2 and 3 mm, the smaller sizes being more common. Normally, the nerve after emerging from the internal meatus broadens in funnel-like fashion and at once enters the medulla. The length available in such cases is usually no more than 2 mm. In a few cases, however, there is a length of nerve as great as 5 or 6 mm, when the meatus is anterior to its usual position, and the nerve runs backward to its junction with the medulla.

The active electrode, usually in the form of a small copper hook, was placed around the nerve, while an inactive electrode was placed elsewhere on the body, in most cases on the severed cerebral tissue or on the muscle of the neck.

In most experiments the left pinna was removed and a rubber tube sewed into the external meatus. The tube led to a funnel into which the stimulating sounds were delivered.

Apparatus.—The nerve currents picked up by the electrodes were conducted from the operating room, where the preparation remained, through about 60 ft of shielded cable to the amplifying and detecting apparatus in the sound-proof room. The upper diagram of Fig. 1 shows schematically the apparatus arrangement. In the sound-proof room the currents were first led to a vacuum-tube amplifier consisting of 2 to 4 resistance-coupled stages and a final power stage, and thence to a telephone receiver. A transformer has been inserted in the input circuit in later experiments to make a better

impedance match between preparation and amplifier. In some cases a voltage attenuator has been interposed between the output of the amplifier and the receiver for measurements of signal strength. All apparatus and accessories were thoroughly shielded.

The amount of amplification varied in different experiments from about 320 times (two stages) to about 100,000 times (four stages). With 320 times the signals were only faintly audible at the receiver. With 100,000 times they were audible at all parts of the room. Usually about 5,800 times (three stages) amplification was used; this gave a signal of comfortable intensity, about 50 TU at 1000~. At the higher degrees of amplification a background of tube noise was present which impaired the reception to some extent.

Results

The results of this series of experiments relate to the nature of response in the auditory nerve as a whole during stimulation of the ear by sound, and apply particularly to the response as correlated with the frequency of the sound. A large number of experiments have been made to rule out the possibility of artifact, and to establish definitely whether the responses obtained are due to nerve action currents.

At the date of this writing we have performed these experiments on 18 animals, and have secured auditory nerve responses from every one of these except the first; the first attempt failed, as we now know, because of insufficient amplification. Three animals during the early experiments died very soon after completion of the operation, and permitted observations for only a few minutes. Then, however, we were employing the customary method of decerebration; since our adoption of the method described above this difficulty has disappeared, and the animals have remained in good condition through many hours of experimentation.

I. The Representation of Sound in the Nerve Response

1. *The frequency correlation.*—The fundamental result of these experiments is the discovery that sounds applied to the

ear of the animal produce effects in the acoustic nerve which correspond in an essential way to the frequency of these sounds. The electrical changes set up in the nerve in the passage of the nerve impulses are such as to produce in the receiving apparatus tones of the same nature as those affecting the auditory apparatus of the cat. In other words, the physiological preparation plays the same rôle here as a sound transmitter in an ordinary communication line. A pure tone sounded into the ear of the cat is recognized as that same tone in the receiver. Speech is received readily; and the degree of fidelity can be judged from the fact that under good conditions an observer in the sound-proof room is able to recognize who is speaking into the cat's ear if the person's voice is reasonably familar to him. Other complex sounds, including noises of all kinds, are received with equal facility, and show further the absence of any great amount of distortion.

The range of tones which we have recorded extends over about five and a half octaves, specifically, from 105 to 5200~. The range obtained in any given experiment depends primarily on the amount of amplification used. This is because the sensitivity of the human ear used as the detecting device falls off greatly for low and high frequencies, and grows particularly poor as the frequency is raised beyond 3000~.[1] We have no reason to believe that 5200~ represents the upper limit of hearing of the animal, and anticipate the demonstration of still higher frequencies.[2]

Throughout the range just mentioned the received frequencies have been shown by direct comparison to correspond to the sound frequencies applied to the ear. For these comparisons a telephone line was set up between operating and sound-proof rooms, and the sound was introduced alternately into the cat's ear and into the transmitter of the telephone system (see the lower diagram of Fig. 1). Under these conditions the accuracy of a frequency comparison may be very

[1] See the normal sensitivity curves determined by H. Fletcher and R. L. Wegel, *Phys. Rev.*, 1922, **19**, 555–565, and C. C. Bunch, *Arch. Otolaryngology*, 1929, **9**, 625–636.

[2] Cats hear tones as high as 10,000 to 20,000~. See E. G. Wever, The upper limit of hearing in the cat, *J. Comp. Psychol.*, 1930, **10**, 221–233.

conservatively rated as within 1 or 2 percent. To the observer the tones are of the same pitch.

The degree of tonal discrimination possible through the animal seems as high as can be expected in the presence of the background noise and with the strength of signals available.

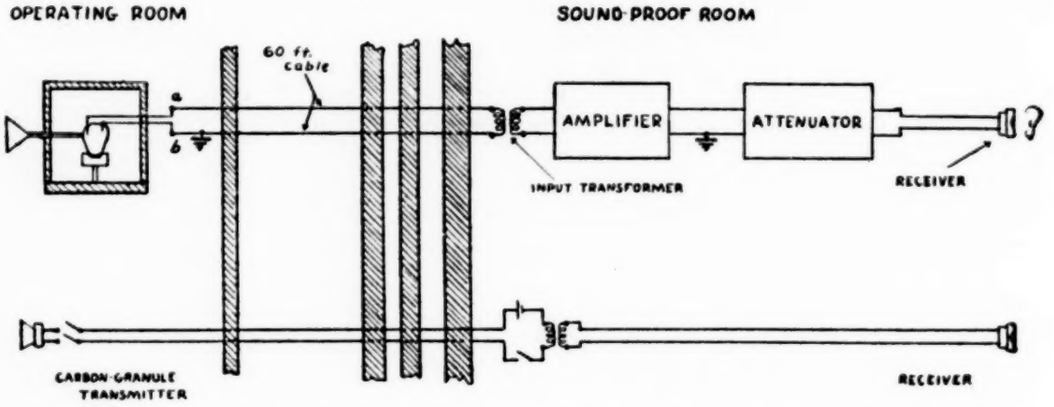


FIG. 1. *Above*, Apparatus for detection of the nerve currents set up through stimulation of the ear by sound. *Below*, Telephone system used for direct comparison of the nerve currents and the stimulating sounds.

That is, we consider the discrimination to be limited more by the conditions of observation than by the transmission properties of the cat's auditory apparatus. Tests with the Galton whistle have shown the tones 3433 and 3373 to be discrimi-

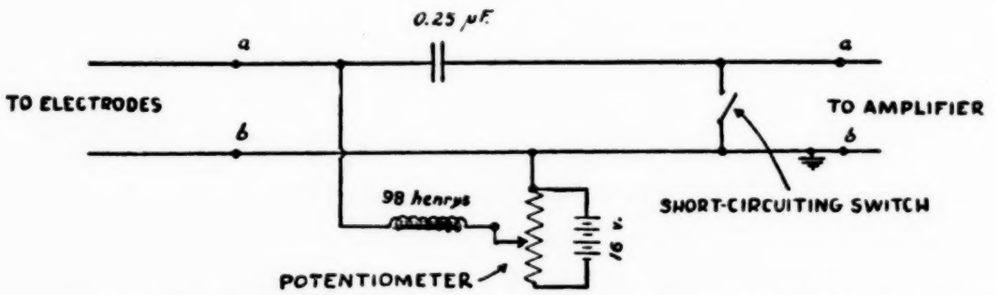


FIG. 2. Circuit arrangement used in the introduction of a polarizing current into the nerve. This apparatus was introduced into the detecting system at the points *a*, *b* in Fig. 1.

nated (difference 60˜) but not the tones 3433 and 3399 (difference 34˜).

2. *The intensity correlation.*—The results of this series of experiments apply chiefly to the relation of the nerve response to stimulation frequency, and give less information

regarding the relation to intensity. The difference is in part a function of the method of recording; the observer's ear is not very sensitive to small changes of intensity. Indeed, the voltage obtained from the nerve would have to change about 25 percent (2 TU) in order to be detected by this method. Some general results can be reported, however.

Within limits at least, the louder the stimulus the stronger the signal received. We have not observed much difference in the use of medium and strong intensities at high frequencies, but whether we are concerned here with the upper intensive threshold of the animal or with the observational limitation just mentioned we cannot say.

Under good conditions a very weak stimulus is adequate. A faint whisper into the cat's ear is easily audible in the receiver. The observer can hear and often understand ordinary conversation between persons in the operating room. The sounds of walking about and the usual manipulation of apparatus are also audible.

As the condition of the preparation becomes poorer, through injury to the nerve, drying or other impairment of the tissues, or through restriction of the blood-supply, the reception becomes worse, and faint sounds are no longer audible. Loud sounds, however, may still be received. After the death of the animal the responses grow progressively fainter, and finally cease.

This evidence indicates some kind of positive correlation between the voltage established in the nerve as a whole and the intensity of the stimulating sound. It does not, however, show the exact functional relationship between these variables.

3. *The magnitude of the auditory response.*—Some preliminary information regarding the magnitude of the response from the auditory nerve was secured by a comparison with responses from muscles and other nerves in the same animal.

For observation of muscle currents a small flexor muscle in the foreleg was selected. When the electrode was applied, and the muscle stretched with forceps, the normal tonic discharge increased rapidly in rate and developed into a definite "roar" of sound. For observation of impulses in peripheral

nerves the radial nerve in the foreleg was first used. A hook electrode was placed around the nerve. A sharp rap on the paw of this leg gave a short dull sound in the receiver. Pressing on the "quick" of a cut toe-nail for a few seconds gave a slow welling-up and then a decay of impulses. An electrode on the vagus nerve gave a constant bombardment which seemed to increase on hampering the breathing of the animal. All these impulses, including those from the muscle, were of the same general order of intensity as those obtained from the auditory nerve. Their rate, however, probably did not exceed 100 per second (Cat 13).

A rough measurement of the intensity of the action currents was made on one animal by means of the cathode ray oscillograph, and yielded a value of 90 microvolts. We mention this figure only to indicate in a very general way the order of magnitude of the nerve voltage, and hope to report more precise measurements later.

II. Experiments Made to Check the Findings

It is necessary in an experiment of this nature to give a large amount of attention to the elimination of the numerous possibilities of artifact. The following checking experiments have therefore been made.

1. *Induction.*—Induction effects are of first importance in the use of a sensitive electrical system if the stimulus is electrical or magnetic in nature. In all the crucial tests recorded here we have avoided such stimulating apparatus, and have been content with the use of the voice supplemented by an array of organ pipes, a small brass whistle variable from 1000 to 3000^{-}, and a Galton whistle ranging from about 3000^{-} upwards. We have not used tuning forks, because we find that if they are placed before the animal's ear in the ordinary way the vibration of their magnetic fields—for they seem invariably magnetized—sets up induced currents in the lead-in wires. They may be used with safety if held a foot or two away, or if protected by an electromagnetic shield. Likewise we have in these experiments avoided the use of audio-oscillators though tests show that they also can be employed if

the animal and electrode wires are carefully shielded. It has been simpler in these preliminary experiments to use wind sources of sound.

2. *Microphonic effects.*—Microphonic effects through vibration of the amplifier tubes by the sound waves were avoided by placing the amplifier within the sound-proof room and the preparation in another room about 50 ft distant. Tests showed the sound-proofing to be adequate.

3. *Mechanical action of the electrodes.*—The first source of artifact that occurs to anyone after induction and microphonics are ruled out is movement of the electrodes in response to the sound. It is very easy to imagine that the pressure-variations of the air cause slight movements of the electrode wires in the tissues, and that these movements produce a change in resistance between the electrodes or a change of interelectrode potential. If the electrodes are placed on dissimilar tissues an interelectrode potential and hence a more or less steady direct current is doubtless present, and changes of the sort suggested would act on the amplifier so as to produce an audible signal corresponding to the stimulus. It is true, one would not expect an electrode wire to respond in very regular fashion to sounds of various frequencies. Yet this possibility deserves considerable attention.

a. Experiments on other tissues.—The most obvious check is placing the electrodes on other tissues. We have placed the active electrode on or under the skin, with the grounded electrode in skin, muscle, or cerebral tissue (cats 2, 4, 9, 10, 18), in muscle, with the grounded electrode in muscle or skin (cats 2, 9, 10, 13, 16), on peripheral nerves (cats 4, 7, 13), and on central nerve tissue away from the acoustic region (cats 2, 4, 8, 10). These tissues never give the response if they are out of the vicinity of the nerve.

The first experiment on peripheral nerves was on the radial nerve of the foreleg. The hook electrode was placed on this nerve in the manner used for the auditory nerve, and the inactive electrode embedded in neighboring muscle or skin tissue. Sounds were produced in the usual way; the acoustic response did not appear (Cat 4). In a second experiment the

saphenous nerve of the hind leg was used in the same manner. As before, the acoustic response did not occur (Cat 7).

Experiments on central nerve tissues apart from the auditory nerve itself were performed on a large number of animals. The responses could always be observed from certain regions of the medulla (cats 9, 10, 11, 12, 13, 15) and from regions of the brain-stem (cats 11, 13, 14, 17) so long as at least one cochlea with its nerve was intact. In nearly all animals the signals disappeared when the electrode was moved off this fairly well-defined system. But this condition is not invariable; we have come across two animals where what we interpret as electrical spread of nerve current was extraordinary, and a third animal where a smaller degree of spread was observed. In the last animal the response was obtained from the cerebellum about ¼ inch from the nerve. In the other two it was obtained from regions much more remote. Extensive investigation was made of these cases.

Cat 11.—Responses were obtained with the electrode under skin, on muscle, or on bone near the ear, but not from such tissues distant from the ear. Responses were obtained from all parts of the cerebellum.

The responses diminished very rapidly in intensity as the electrodes were moved to tissues away from the meatus and temporal bone. They were perceptible at a distance of ½ inch from this region, but not at a distance of 1 inch. The focus of intensity appeared to be at the nerve.

Cat 18.—Responses were obtained from cerebral tissue both before and after decerebration, from temporal and parietal bone, and from skin and muscle in the temporal region. They were not obtained from tissues off the head.

It is peculiar that certain animals show this pronounced spread; to account for it we can suggest only that in these animals the auditory nerve action currents were unusually strong.

b. Death of the animal.—The death of the animal is followed first by a decrease in the intensity, and finally by a complete cessation of the response. The time after death required for complete cessation is of the order of 15–20 minutes (cats 3, 5, 17).

c. Cochlear destruction.—Destruction of one cochlea causes a noticeable reduction in the intensity of the response if the active electrode is on the nerve of that side; the response is still obtainable, however, passing from the opposite cochlea across the medulla. (The electrode around the nerve was in contact also with the side of the medulla, and the impulses were probably picked up through that contact, or else through electrical spread.) (Cat 4.) If the electrode is on one side, and the cochlea of the opposite side is destroyed, no change in the response is observed (Cat 6). If the electrode is in the medulla (cats 10, 12, 13, 15) or on the brain stem (Cat 11) a reduction of intensity is observed on the elimination of one cochlea. The response in all cases disappears when both cochleas are destroyed (cats 4, 6, 10, 15).

d. Restriction of the blood supply.—When the carotids were tied, the blood supply to the head could be shut off by holding the vertebral arteries with the fingers. Such restriction of the blood supply caused usually a reduction in intensity and in some cases a cessation of the response. The results of the different trials varied, largely because of the difficulty in maintaining a sufficient pressure on the vertebral vessels. Out of six trials on cat 8, two resulted in a reduction of intensity, and four in cessation of the response. Of three trials on cat 11, the first gave a reduction of intensity, the second was doubtful, and the third caused cessation. One trial on cat 15 caused a reduction of intensity. In the more successful trials where a firm pressure on the arteries was maintained, the response diminished gradually and disappeared in about 30 seconds; after release of the arteries it returned quickly, taking only 5 or 6 seconds to attain practically its normal magnitude.

Whether this phenomenon is the result of oxygen starvation of the nerve tissues or of changes in the auditory mechanism is not clear; the experiment is valuable, however, in indicating the physiological nature of the response.

e. The effect of a polarizing current.—An apparatus was devised for the introduction of a steady direct current into the nerve through the same electrodes used for leading off the nerve currents. The electrical arrangement is shown dia-

grammatically in Fig. 2. The use of one pair of electrodes for both the polarizing current and detection of the nerve currents was made possible by the insertion of a condenser to keep the direct current out of the amplifying system and a high inductance choke coil to prevent by-passing the nerve currents through the direct current supply. The short-circuiting switch was used during adjustments of the potentiometer to protect the observer's ear. The apparatus shown in the diagram was introduced between the animal and the input leads, at the points *a*, *b* in Fig. 1.

In this experiment the active electrode was on the auditory nerve and the inactive electrode in cerebral tissue. It was found that the polarizing current reduced or eliminated the response. Voltages of 4–8 v. were adequate for complete elimination. Several trials were made with both directions of current, with positive results in every case. As soon as the polarizing current was removed the nerve response reappeared (Cat 8).

This experiment is of value in indicating that the response is of nervous origin. The reduction and elimination of the response by the polarizing current is probably an electrotonic effect on the nerve leading to a conduction block.

4. *Mechanical action of the cochlea.*—The above evidence we consider effectively to eliminate mechanical action at the electrodes, and to indicate the cochlear origin of the effects. The suggestion was made to us, however, that these checks are less effective against the possibility that the effects originate in the cochlea, but are nevertheless mechanical and not nervous. That is, it may be supposed that the cochlea, being specially sensitive to aerial pressure-variations, picks up and transmits these variations to the substance of the nerve in a mechanical fashion, and the resulting movements of the nerve against the electrode vary the interelectrode potential and thereby produce the response.

Against this possibility it can be argued that nerve substance is a poor mechanical conductor, and this would be especially true of the auditory nerve, since it originates in small filaments which later unite into the large trunk emerging

from the internal meatus. Moreover, some evidence against the possibility has already been shown. The cessation of the response on the death of the animal and on the introduction of a polarizing current into the nerve argues against mechanical action of this kind, as it seems unlikely that such action should be seriously impaired by these changes. More positive evidence was obtained in experiments described below.

a. The matter of interelectrode potential.—The type of artifact just mentioned would require the presence of an interelectrode potential. Certainly under ordinary conditions, where the two electrodes are on dissimilar tissues, such a potential is the rule. An effort was made, therefore, to reduce or eliminate such a potential as a check against the artifact suggested.

In certain experiments non-polarizable electrodes of the silver chloride type were used, one on the nerve and the other in the cerebrum. The response continued as before. Two silver chloride electrodes were then embedded in an insulating cement at a distance of 2 mm, and both placed in contact with the nerve. By this means we sought to avoid an interelectrode potential by having the electrodes on similar and adjacent tissue, and by the embedding cement to avoid the possibility of alterations of the distance between the electrodes through any movements in their neighborhood. The responses continued as strongly as before, but perhaps with a certain amount of distortion. It occurred to us that such distortion might be the result of the reception of diphasic action currents (Cat 10).

b. The path of transmission.—The fact that, with the exceptions mentioned above, the response is fairly well localized in certain tracts of the nervous system tells against any hypothesis of mechanical transmission. The currents can be picked up across the medulla and from the brain stem, at distances which would seem too great for mechanical action to be effective. Under the same conditions, other tissues equally distant from the nerve do not give the effects.

c. The cotton-and-film experiment.—The exceptional cases just referred to, in which the response was obtainable from

tissues off the nervous system, happily supplied the opportunity for one of the best checks that we have made. In two animals, as described above, the response was secured with the electrodes on any tissues in the immediate vicinity of the ear. It was found that the active electrode placed on a lump of wet cotton resting on the temporal bone, and the inactive electrode on distant muscular tissue, picked up the responses readily. But if a piece of dry collodion film were interposed between the cotton and the bone the responses disappeared. Yet if a small strand of the cotton were picked up with forceps and carried over the edge of the film so as to make contact with the moist bone or muscular tissues beneath, the response returned. The bit of cotton could be used as a switch to control the response (cats 11, 18). The experiment yielded the same results if both electrodes were on the cotton (Cat 11).

As the manipulation of the strand of cotton did not alter the mechanical features of the situation in any essential manner, we may conclude that the transmission concerned is electrical rather than mechanical in nature.

5. *The source of the electrical effects.*—The following experiment was made to ascertain whether the electrical effects shown to be correlated with the sound have their source in the sense organ or in the nerve. The evidence above, except for that pertaining to the path of transmission, is not relative to this point. The nature of the path of transmission does, however, indicate nerve impulses rather than impulses from the sense-cells of the cochlea. As mentioned above, the responses are fairly well localized in certain nervous tracts, which would hardly be expected if they were being picked up through electrical spread from the cochlea. Also, the distances involved in the transmission across the medulla and to the anterior surface of the brain stem are great for such spread. The following experiment seems to us to add conclusive evidence in favor of nerve transmission.

The right cochlea was destroyed completely, and the impulses tested from both the left nerve and the brain stem. The left auditory nerve was then severed. The responses were no longer obtainable from the brain stem. They were

still obtainable from the stump of the left nerve, however, and continued to be so for some time. Just after severing the nerve the responses from the stump were of normal intensity, but the intensity died away during the next few minutes, and finally the signals ceased.

Care was taken in the transection of the nerve to leave the tissues in contact, and a quantity of salt solution was introduced before and after the transection; it seems reasonable to say that the electrical conductivity of the tissues was not appreciably altered by severing the nerve. As the responses were completely eliminated, our conclusion is that these responses are due to nerve conduction (Cat 11).

Summary

By placing electrodes on the exposed auditory nerve of the cat the writers have observed the responses set up through stimulation of the ear by sound. A correspondence between the frequency of the sound and the frequency of the response has been demonstrated. A number of experimental checks have been made, establishing the response as due to action currents in the auditory nerve.

(Manuscript received May 22, 1930)

INTENSITY OF LIGHT AND SPEED OF VISION

BY C. E. FERREE AND GERTRUDE RAND

Research Laboratory of Physiological Optics, Wilmer Ophthalmological Institute, Johns Hopkins Medical School

II. Comparative Effects for Dark Objects on Light Backgrounds and Light Objects on Dark Backgrounds

The present paper is a continuation of the program of work outlined in the first paper published under the above title.[1] In that paper the effect of change of intensity of light over a wide range on the speed of vision was studied in the presence of two important variables: size of object and difference in cœfficient of reflection between object and background. Sizes of object were chosen subtending visual angles of 1, 2, 3, 4.2 and 5.2 min and having cœfficients of reflection of 3–4 percent. The cœfficients of reflection of the backgrounds were 78, 29, 21 and 16 percent. The visual angles selected were considered representative of sizes of work for which changes of intensity of light have an important ocular effect; the cœfficients of reflection of the backgrounds are, respectively, approximately those of a white surface of good reflecting power, polished brass and steel, unpolished brass and steel, and iron. The range of illuminations covered extended from 1.25 to 100 ft c. The determinations were made with the special purpose of obtaining information on the following points: (1) the comparative importance of changes in size of object, difference in cœfficient of reflection between object and background, and intensity of illumination as factors influencing the speed of the eye's response; (2) the influence of size of object and difference in cœfficient of reflection between object and background on the range of speeds given by the

[1] C. E. Ferree & G. Rand, Intensity of light and speed of vision. I. Effect of size of object and difference of coefficient of reflection between object and background, this Journal, 1929, 12, 363–391.

illuminations selected; and (3) the influence of both of these factors on the shape, sharpness of inflection and location of the knee of the curve representing the change in the speed of the eye's response. In addition special consideration was given to the comparative benefit of increase of illumination at various points in the intensity scale.

Among other points with regard to which the need of further laboratory study was felt, the following were mentioned in that paper: (1) the effect of certain typical or representative differences in color between object and background; (2) a comparison of the effect of a dark object on a light background and a light object on a dark background; (3) a determination of the effect of the position of the difference between object and background in the scale of cœfficients of reflection; (4) the influence of the form and complexity of object and the degree of complication of the task set for the eye; (5) the ratio of speed of vision to the speed of the visual-motor reaction over a wide range of intensities of illumination and the influence of change of intensity on this ratio; (6) a comparison of the time required for the eye just to discriminate its object with the time which it actually takes in making the discrimination in a series of visual acts when working at maximum speed; and (7) a more complete analysis and evaluation of the factors which affect acuity and speed of vision, more particularly in relation to their influence on the effect of intensity of light.

In the present paper only the second of the points mentioned above was studied. In the study of this point the effect of intensity of light was investigated for light objects on dark backgrounds and a comparison made with the effect for dark objects on light backgrounds. Two cases were made of this, —white test-objects on a black background reflecting 4 percent, of the incident light for comparison with the former study of black test-objects on a white background; and white test-objects on a gray background of approximately the brightness of unpolished steel (21 percent cœfficient of reflection) for comparison with the former study of black test-objects on a gray background of this cœfficient of reflection. Broken circles subtending visual angles of 1, 2, 3, 4 and 5 min were used as

test-objects in both cases. It was found as the work progressed, however, that the speeds were so high for the white objects on the dark backgrounds that it was impracticable to work with visual angles larger than 3 min.

Other points included in the present paper are: (1) a study of the cause of the difference in speed and in the shape of the curves showing the effect of intensity on speed, obtained for dark objects on light and for light objects on dark backgrounds; and (2) the individual differences for four observers in the speed of seeing white and black objects on gray backgrounds of the same cœfficient of reflection.

The Effect of Increase of Intensity of Light on Speed of Vision for White Objects on Dark Backgrounds and a Comparison of this Effect with that for Black Objects on Light Backgrounds

The purpose of this series of experiments was to determine the effect of increase of intensity of light on speed of vision when objects lighter than the background were used. Commercial and other practical applications for data of this kind may be found in the various textile industries where white threads are woven against backgrounds differing in brightness; in the reading of photostat sheets; in the formulation of the specifications for the ideal printed page; in the selection of combinations of object and background for certain types of test chart, signs, signals, license plates, tags, reading scales of instruments and other designations requiring a high visibility; etc.[1]

The experiments were planned to duplicate these various practical conditions as closely as possible in their more essen-

[1] Writing on the subject of the combination of light on dark or dark on light, Henry D. Hubbard, Chief of the Division of Printing and Engraving, Bureau of Standards, says: "Motion picture legends early changed from dark on light to light on dark because of the eye shock of a brilliant white screen following quickly, perhaps, after a night scene. The scale of aviation instruments and of many automobile switchboard instruments have made a similar change to light on dark. Advertisers realize and use the striking effects of light on dark. The proposed re-use of newspapers suggested years ago as a measure of waste saving, involved the use of black paper with white ink to save the bleaching process and ink removal otherwise required. Blueprints and photostats have accustomed us to light on dark."

tial points. Test-objects (broken circles) subtending 1, 2, 3, 4, and 5 min visual angles were carefully prepared for the work under the direction of Professor J. W. Barker at the Massachusetts Institute of Technology. A black test-object was drawn to scale and photographed with the minification necessary to give detail which would subtend the desired visual angles at 2.5 meters. Both positive and negative plates were made so that either black letters on a white ground or white letters on a black or a gray ground could be printed. To obtain the brightness of background desired with the white test-letters, the positive plate was used and the exposure carefully timed to give the brightness desired. After considerable experimentation a series of test-objects of the sizes selected was produced on backgrounds which varied in reflection cœfficient by less than 1 percent. In order to provide material from which pre-exposures which matched the backgrounds could be made, large sheets of sensitive paper were also exposed for the same length of time as the test sheets. The white test-objects used in the present study were on gray backgrounds of approximately the brightness of unpolished steel (21 percent cœfficient of reflection) and on black grounds (4 percent cœfficient of reflection.) The test-objects themselves reflected 78 percent of the incident light. The objects and their backgrounds were given a matt finish. The experimental room, conditions and method of work, observer, etc. were the same as for the previous study in which the effect of increase of intensity was investigated for black test-objects on white and gray backgrounds. In every case the pre-exposure was to the same brightness as the background on which the test-object was viewed.

As the work progressed it became evident that the speeds for the white test-objects on the dark grounds were greatly in excess of those for the dark objects on the light grounds when large visual angles and high intensities were used. In fact the exposure-times needed to discriminate the 5-min detail were shorter than could be obtained within the range of the sensitive setting and reading of our tachistoscope. It was decided, therefore, to limit the study to a determination of the effect for only the 1, 2, and 3 min visual angles.

The results are given in Fig. 1. These curves are plotted to the same scale as the mass curves for the twenty conditions of black test-objects on light backgrounds given in Fig. 1, of the previous paper (p. 369). For the sake of comparison the following curves of that study are reproduced in the present chart: 1, 2, 3 and 5 min black test-objects on white (78 percent cœfficient of reflection) and 1, 2 and 3 min black test-objects on gray (21 percent). The new curves are for 1, 2 and 3 min white test-objects on black (4 percent cœfficient of reflection) and 1, 2 and 3 min white test-objects on gray (21 percent). In this and the following charts, the experimental points determined for the black test-objects are indicated by dots, and for the white test-objects by circles; the curves for the gray backgrounds are plotted in broken lines and for the white and black backgrounds in solid lines.

Among the points to be noted in these curves are (1) the high speeds obtained with large visual angles and large differences in cœfficient of reflection between object and background; (2) the more rapid initial rise of the curves for the large than for the small test-objects; (3) the higher speeds obtained in general for white objects on black than for black objects on white backgrounds, and for white than for black objects on gray; and (4) the flattening of the curves at the higher intensities for dark objects on light, as compared with light objects on dark backgrounds.

In order that the results may be studied in greater detail, Fig. 2 has been prepared for the four conditions of test-object and background used with each of the three visual angles. In these charts the following points are brought out: (1) the shorter time needed to discriminate the 1-min black test-object on white at low intensities, as compared with the 1-min white test-object on black; (2) the longer time needed to discriminate the 1-min black test-object on white at high intensities, as compared with the 1-min white test-object on black; [1]

[1] In work done on speed of discriminating a black test-object on a white field and a white test-object on black both in the present study and in an unpublished investigation made in 1924, we have found that for small sizes of object (1 min visual angle or less) and low intensities, speed of discrimination is higher for black on white than for white on black; but that for larger sizes of object and high illuminations,

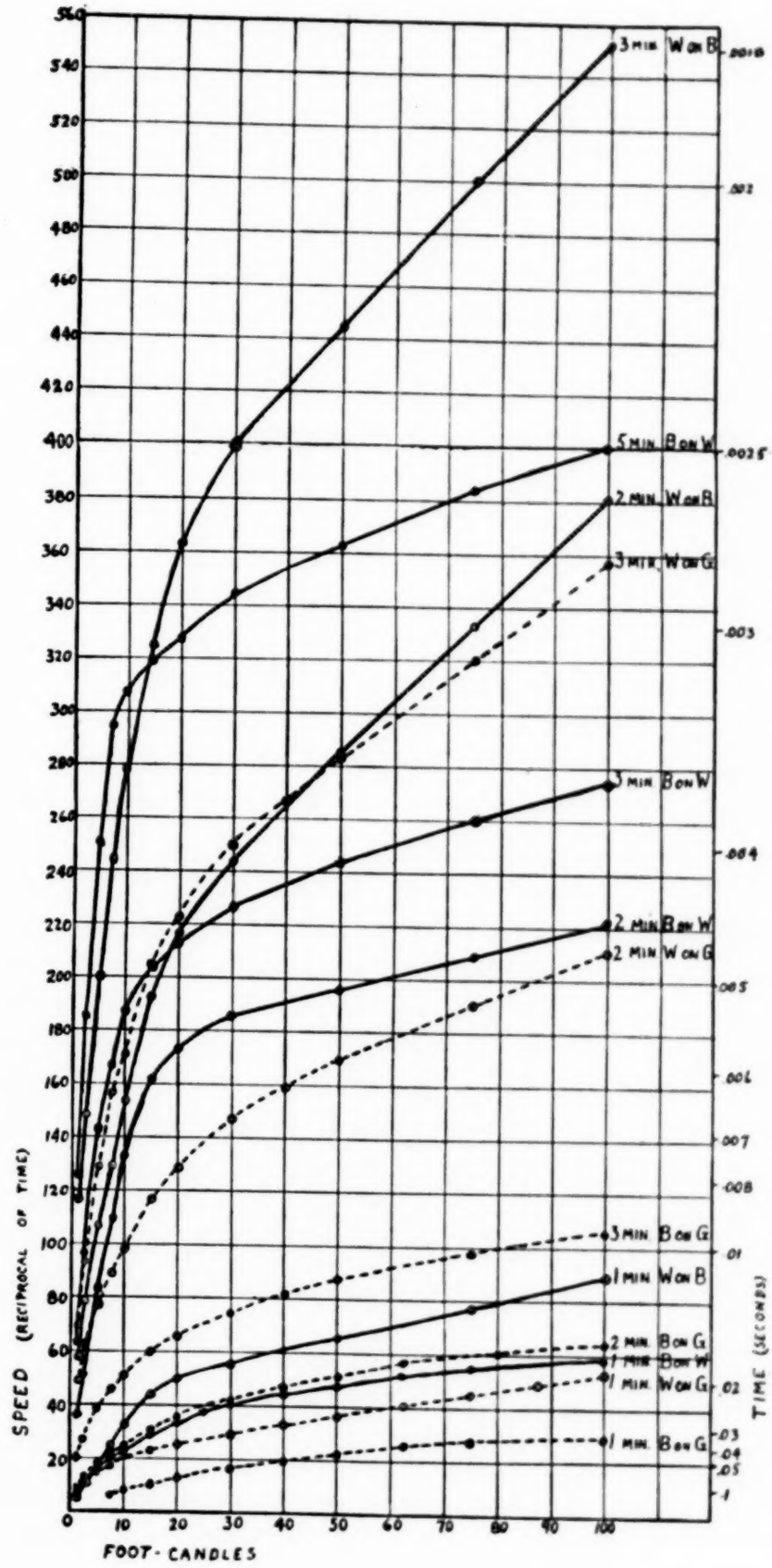

SPEED (RECIPROCAL OF TIME)
TIME (SECONDS)
FOOT-CANDLES
3 MIN W ON B
5 MIN B ON W
2 MIN W ON B
3 MIN W ON G
3 MIN B ON W
2 MIN B ON W
2 MIN W ON G
3 MIN B ON G
1 MIN W ON B
2 MIN B ON G
1 MIN B ON W
1 MIN W ON G
1 MIN B ON G

FIG. 1. Curves showing for gross comparison the results obtained on the effect of increase of intensity of illumination on speed of vision for the following cases: 1, 2 and 3 min white test-objects on black background; 1, 2, 3 and 5 min black test-objects on white background; 1, 2 and 3 min white test-objects on gray background; and 1, 2 and 3 min black test-objects on gray background.

(3) the higher speeds obtained for white than black test-objects on gray at all intensities and with all visual angles; (4) the greater effect of increase of intensity on speed for white objects on black than for black objects on white, particularly in case of small objects; and (5) the flattening of the curves at the high intensities for the black test-objects on white and gray, as compared with white test-objects on black and gray.

With reference to the above points the following explanations are suggested:

(1) *The shorter time needed to discriminate the 1-min black test-object on white at low intensities as compared with the 1-min white test-object on black.*—Determinations of the speed of discriminating 1 min detail at low intensities are made in the region of the threshold of acuity. It would be expected, therefore, that the comparative results would be similar to those of acuity determinations. Acuity is found by test to be higher for black letters on white than for white letters on black. This result is probably due to the phenomenon of irradiation in the image formed on the retina. That is, the image of a white object by irradiation spreads or encroaches on the black background, thus becoming larger; while in case of the black object, the image of the background spreads or encroaches on the unstimulated area corresponding to the black object and renders it smaller. The result is that while the black letter appears smaller on the white ground than the white letter on the black, the detail to be discriminated, *i.e.*, the opening in the circle, appears larger on the white than the black background. In determinations of clear seeing and of speed of discrimination made at or near the acuity threshold, therefore, where space discrimination is a very important factor in the result, the apparently larger detail is sufficient to give better powers of discrimination in case of black on white than of white on black.

it is higher for white on black than for black on white. For Observer R whose resullt are published in the present study, the point of transition comes for a 1-min visuas angle at 5 ft c. For this observer shorter times of exposure are needed to discriminate detail in a 1-min black test-object below 5 ft c and longer above 5 ft c than for a 1-min white test-object on black. In the unpublished investigation results were obtained for 5 observers for 1 min test-objects and intensities ranging from 0.4 to 12 ft c. For all observers the point of transition occurred between 2 and 8 ft c.

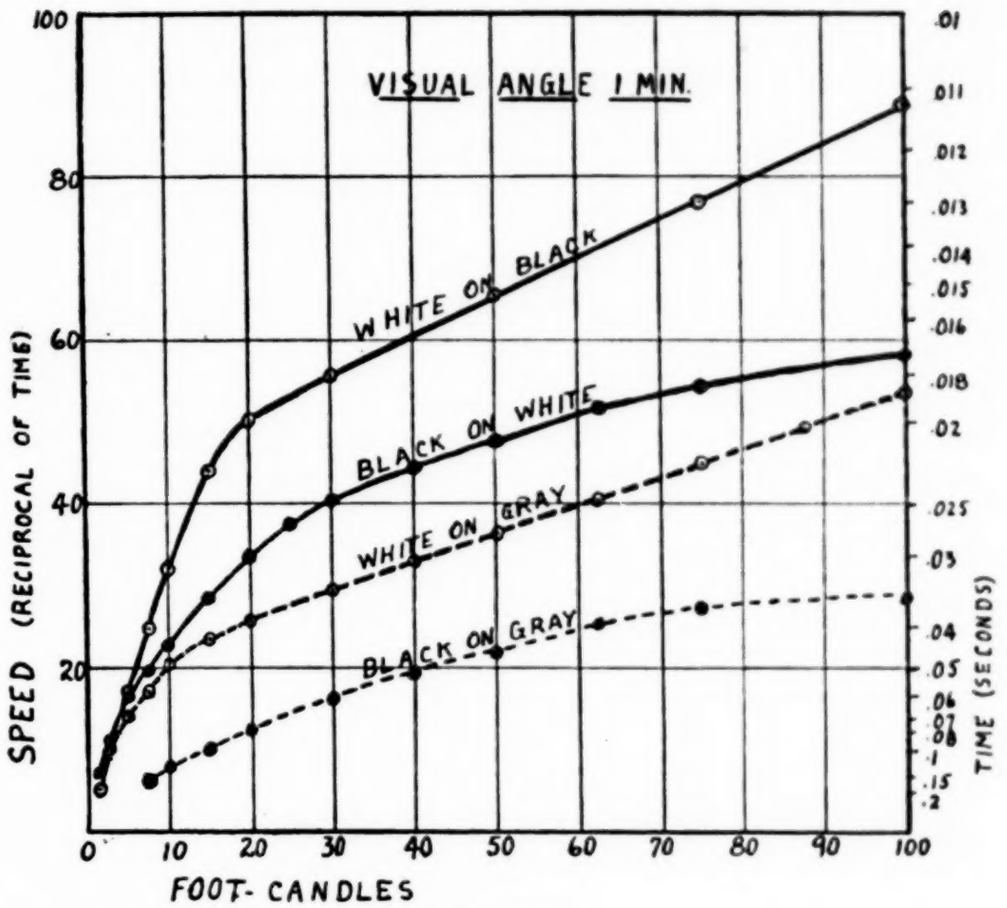


CHART 1.

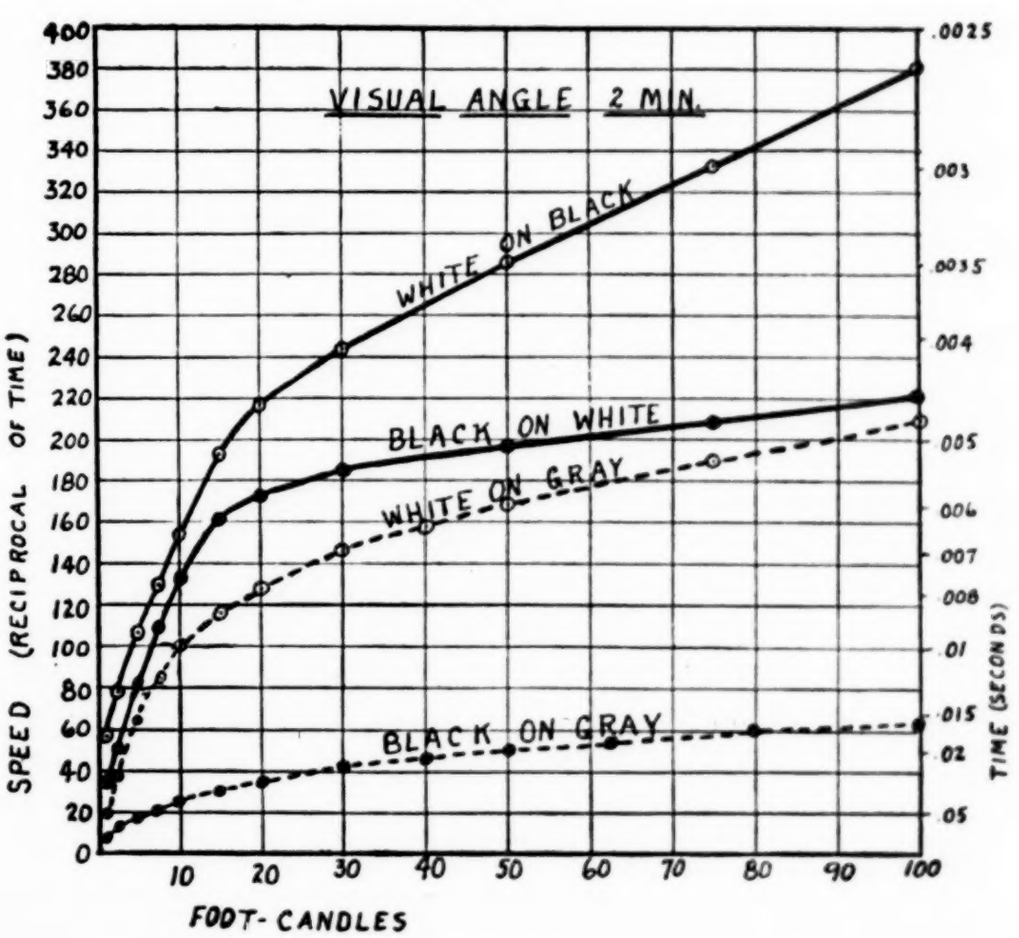


CHART 2.

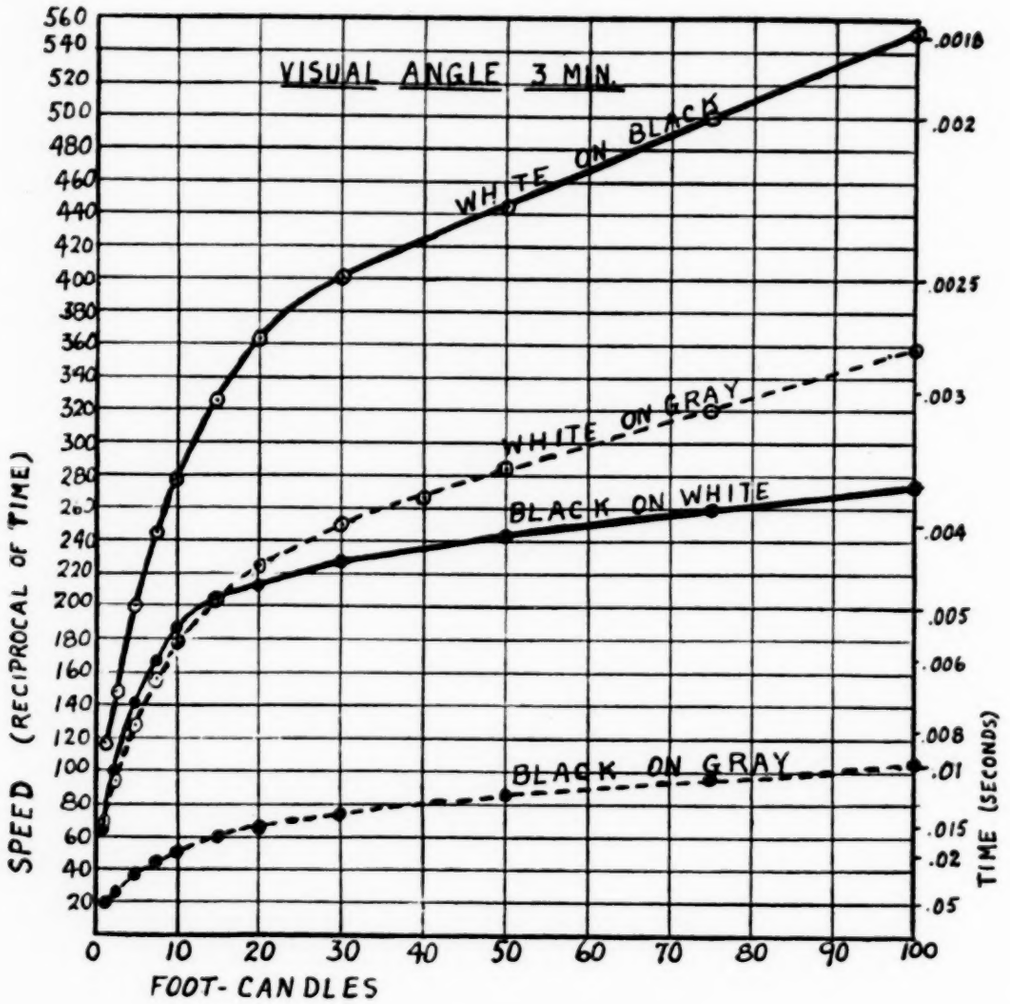


CHART 3.

FIG. 2. Curves showing the comparative effects of increase of intensity of illumination for the four conditions of object and background. Charts 1, 2 and 3 give respectively the results for 1, 2 and 3 min visual angles.

DATA FOR CURVES IN FIG. 2

Chart 1: Visual angle 1 min

Illumination (ft c)	White on Black		Black on White		White on Gray		Black on Gray	
	Time of discrim'n (sec)	Speed (Recip'al of time)	Time of discrim'n (sec)	Speed (Recip'al of time)	Time of discrim'n (sec)	Speed (Recip'al of time)	Time of discrim'n (sec)	Speed (Recip'al of time)
1.25	0.182	5.5	0.1500	6.7	0.1923	5.2	.....	.....
2.50	0.098	10.2	0.0886	11.3	0.1111	9.0	.....	.....
5.00	0.0581	17.2	0.0608	16.5	0.0704	14.2	.....	.....
7.50	0.0402	24.9	0.0508	19.7	0.0574	17.4	0.160	6.3
10.00	0.0312	32.2	0.0442	22.6	0.049	20.4	0.0124	8.1
15.00	0.0227	44.1	0.0350	28.6	0.0426	23.5	0.0996	10.0
20.00	0.0199	50.3	0.0300	33.3	0.0389	25.7	0.0813	12.3
30.00	0.0180	55.6	0.0249	40.2	0.034	29.4	0.0620	16.1
50.00	0.01534	65.2	0.0210	47.6	0.0274	36.5	0.0455	22.0
75.00	0.01295	77.2	0.0184	54.4	0.0223	45.0	0.0367	27.3
100.00	0.01125	88.9	0.01725	58.0	0.0188	53.2	0.0348	28.7

Chart 2: Visual angle 2 min

1.25	0.0173	57.8	0.0283	35.3	0.051	19.6	0.121	8.3
2.50	0.01275	78.4	0.0195	51.3	0.0268	37.3	0.0738	13.0
5.00	0.0094	106.4	0.0121	82.6	0.0157	63.7	0.055	18.2
7.50	0.00775	129.0	0.0091	109.9	0.0119	84.0	0.0455	22.0
10.00	0.0065	153.9	0.0075	133.3	0.0010	101.0	0.0398	25.1
15.00	0.0052	192.3	0.0062	161.3	0.0086	116.3	0.0333	30.0
20.00	0.00463	216.2	0.0058	172.4	0.0078	128.2	0.0287	34.8
30.00	0.0041	243.9	0.0054	185.2	0.0068	147.1	0.0240	41.7
50.00	0.00352	283.7	0.0051	196.1	0.0059	169.5	0.0195	51.3
75.00	0.0030	333.3	0.0048	208.3	0.00525	190.5	0.01684	59.4
100.00	0.00262	381.7	0.0045	222.2	0.00475	210.5	0.0157	63.7

Chart 3: Visual angle 3 min

1.25	0.0086	116.3	0.0160	62.5	0.0143	69.9	0.050	20.0
2.50	0.00675	148.2	0.0104	96.2	0.01075	93.0	0.0382	26.2
5.00	0.0050	200.0	0.0070	142.9	0.0078	128.2	0.0260	38.5
7.50	0.00410	243.9	0.0060	166.7	0.0064	156.3	0.0218	45.9
10.00	0.00360	277.8	0.00535	186.9	0.00562	177.9	0.0196	51.0
15.00	0.003075	325.2	0.00490	204.1	0.00487	205.3	0.0167	59.9
20.00	0.00275	363.6	0.00470	212.8	0.00444	225.0	0.0153	65.4
30.00	0.00250	400.0	0.00440	227.3	0.00400	250.0	0.0135	74.1
50.00	0.00225	444.4	0.00410	243.9	0.00353	283.3	0.0115	87.0
75.00	0.0020	500.0	0.00385	259.7	0.003125	320.0	0.01025	97.6
100.00	0.00181	552.5	0.00365	274.0	0.0028	357.1	0.0095	105.3

(2) *The longer time needed to discriminate a 1-min black test-object on white at high intensities and 2 and 3 min black test-objects on white at all intensities, as compared with white test-objects on black.*—Determinations of speed of discriminating 1-min detail at high intensities and 2 and 3-min detail at all intensities are made well above the threshold of acuity,—the particular level in any case depending on the acuity of the observer, the size of test-object, the intensity of illumination, and the ratio of cœfficient of reflection between object and background. In these cases small differences in size of detail would not be expected to be as strong a factor in the total result as at the threshold of acuity. Two other factors are apparently of greater importance at these supraliminal levels. (*a*) There is a greater difference in sensation between object and background in case of white on black than black on white, due probably to physiological induction or contrast. Sensation difference is, we believe, the more important factor in speed of discrimination at high intensities and with large test-objects; and space discrimination at low intensities and with small test-

objects. That there is a greater sensation difference in case of the white test-object on black than for black on white is demonstrated later in the paper. And (*b*) the persistence of the sensation aroused by the pre-exposure (the positive after-image) tends to obscure the test-object more in case of black on white than white on black. That this is true will also be demonstrated later in the paper. The occurrence of an after-image following the pre-exposure can not be avoided either in laboratory tests or in the ordinary use of the eyes. The eye always carries over an impression of what it has previously looked at, and the new sensation can develop only as the former impression dies away. When the exposure-time of the stimulus is comparatively long, *e.g.*, of the order of seconds, the effect of the pre-exposure is expressed first in the positive, then in the negative phase of the after-image. When, on the other hand, the exposure-time is very short, of the order of thousandths of a sec, as is the case in speed tests particularly when large test-objects and high intensities are used, the positive after-image of the pre-exposure alone is superimposed on the test-letter in progressively diminishing intensity, lasting in some cases during the entire time of exposure. When for example, a black letter on a white background is used, the white pre-exposure gives no after-image on the background, but a strong wash of white overlies the test-letter. White, as we know, has a strong masking action on black. This is so marked that in the experiments to be described below, a 3-min black test-object was not visible with an exposure of less than .00308 sec at 50 ft c and of .00612 sec at 5 ft c. When on the other hand a white test-object on a black background is used, the black pre-exposure gives no after-image on the background, but a wash of black overlies the test-letter.[1] Black

[1] It is recognized of course that some writers may not agree that a positive after-image occurs following a pre-exposure to black. Whether it does or not is a matter of interpretation. The position is taken here that black is a sensation and as such the physiological condition which gives rise to it may show inertia or persist. The important thing of course is the relation which type of pre-exposure sustains to the rate of rise of the subsequent sensation, shown by our results. If it is held that black does not give a positive after-image, the curves given for this type of pre-exposure must of course be considered to represent the rise of the subsequent sensation unobscured by an after-effect.

as pre-exposure, however, apparently does not have as strong an inhibitive action on the succeeding white excitation as white has on the black. With an exposure-time of only .00145 sec at 50 ft c a faint sensation was obtained from the white letter on the black ground, in contrast to the exposure of .00308 sec which was needed for the black letter to be just visible on the white ground; and at 5 ft c only .00251 sec was needed, in contrast to .00612 sec.

(3) *The higher speeds obtained for white than black test-objects on the gray background at all intensities and for all visual angles.*—Two explanations are offered for this result. (*a*) The gray background used is nearer to the black than to the white test-letter in sensation value. There is, therefore, greater contrast between object and background in case of the white than the black test-letter. There is moreover probably a greater sensation difference between object and background in case of the white test-object due to physiological induction or contrast. (*b*) The persistence of the sensation aroused by the pre-exposure tends to obscure the black letter more than the white. The gray pre-exposure produces no after-image on the gray background in either case, but gives a wash of gray over both test-letters. This gray after-image obscures the sensation from the black test-object much more strongly than from the white. All of these facts serve to render the white letter more visible on the gray background than the black letter.

(4) *The greater effect of intensity on speed for white objects on black than for black objects on white.*—Two reasons may be offered for this. (*a*) With a given difference in cœfficient of reflection between object and background, the visual or sensation difference increases rapidly with increase of intensity of illumination. This increase as will be shown later in the study, is more rapid for a white object on black than for a black object on white. And (*b*) there probably is less increase of the inhibitive or masking action of the pre-exposure with increase of intensity of illumination for the white object on the black background than for the black object on the white background.

(5) *The flattening of the curves at the high intensities for the*

black test-objects on white and gray backgrounds as compared with white test-objects on black and gray backgrounds.—At the high intensities, particularly with large test-objects, the time of discrimination is very short. Under these conditions the persistence of the sensation aroused by the pre-exposure would occupy a greater proportion of the total time of the exposure and would have a relatively stronger obscuring effect than under conditions which require longer exposure. The black test-letter on the white background under the influence of the white pre-exposure will, therefore, be obscured relatively more at high than at low intensities, as compared with the white letter on the black background under the influence of the black pre-exposure. The curves for the black letters will, then, be flattened at the high intensities more than the curves for the white letters.

The Effect of Brightness of Pre-exposure on Speed of Discrimination

With reference to the explanation of the above points, two investigations were made, one to show the effect of the brightness of the pre-exposure on speed of discrimination; the other to show in just noticeably different steps the dying away of the positive after-image of the white and black pre-exposures, or the rate of rise of the sensation aroused by the test-object when these pre-exposures are used.

In the first of these investigations, the time needed to discriminate the 3-min black test-object on white and on gray and the 3-min white test-object on black and on gray was determined for two intensities 5 and 50 ft c., using pre-exposures in each case of white, black and gray. When for example, the black test-letter is used on the white background, the white pre-exposure would have comparatively little or no effect on the background, but through its after-image would lighten and obscure the test-letter; the black pre-exposure would darken the background and have comparatively little or no effect on the test-letter; the gray pre-exposure would darken the background and lighten the test-letter. Similarly the situation can be worked out for each condition of letter and back-

ground used. In every case the effect is to decrease the brightness difference between object and background. The results are given in Table I. This table shows that there is a very strong effect of the pre-exposure on speed of vision. The speed is always highest with the black pre-exposure, lowest with the white, and intermediate with the gray.

The question may be raised why we used the condition of pre-exposure chosen in our work, *i.e.*, a pre-exposure which matched the background in brightness. We have always used this condition because we believe that it most nearly duplicates the actual conditions of seeing. Whether or not our belief is correct, the point is clear that a full knowledge of the relation of intensity of light to speed of vision can not be had until curves showing the relation of intensity to speed are determined for other conditions of pre-exposure than have been used up to the present time.

The Effect of Brightness of Pre-exposure on the Rate of Rise of the Sensation Aroused by the Test-object

In the second investigation an attempt was made to trace the course of the positive after-image of the white and black pre-exposures at 5 and 50 ft c. For this work the exposure-time was determined which was needed to give successively in just noticeably different steps more intense sensations of the test-letter. In one set of experiments, two 3-min black test-objects were mounted side by side on the white background and a sector whose radius was such that its outer edge bisected the space between the two letters was added to the tachistoscope. The white pre-exposure was used. The procedure was as follows. The exposure-time was determined which gave the first trace of sensation from the test-letters. This gave the first point in the curve representing the dying away of the positive after-image of the white pre-exposure or the rise of the sensation aroused by the black test-object under the influence of the white pre-exposure. This value of exposure was then given to the sector of shorter radius, and the outer sector was widened until a just noticeably stronger sensation was obtained from the longer exposed test-letter than from the

shorter. This gave the second point in the curve. The procedure was repeated until it was evident that a further widening of the sector, *i.e.*, lengthening of the exposure-time, within the limits of the exposure-times used in our investigations of speed of vision, would produce little if any increase in the sensation. In another series of experiments, similar data were obtained for two 3-min white test-objects on the black back-

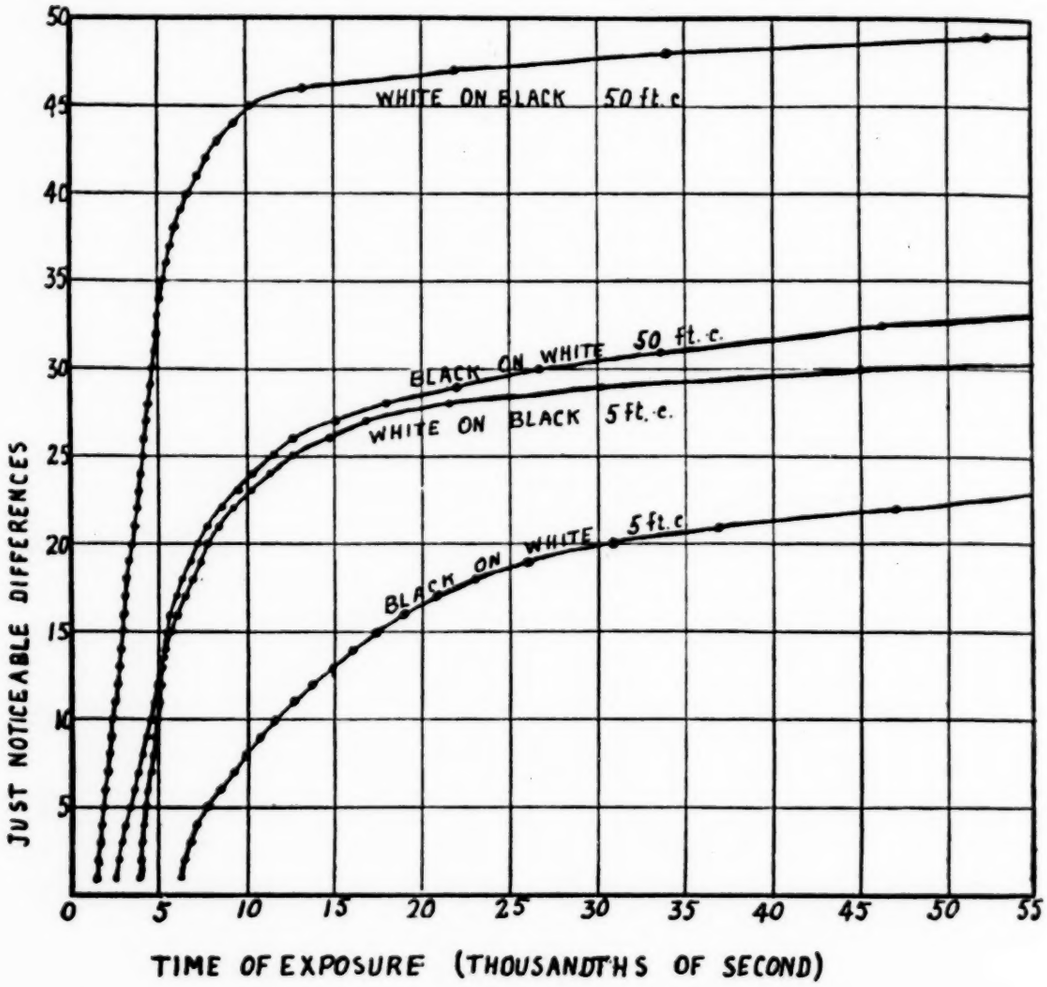


FIG. 3. Curves showing in just noticeably different steps the dying away of the positive after-image of the white and black pre-exposures, or the rate of rise of the sensation aroused by the test-object when these pre-exposures are used. Illuminations 5 and 50 ft c. Test-object 3 min visual angle.

ground. In these experiments a black pre-exposure was used. In all, four curves were determined: (*a*) for the black test-object on white with the white pre-exposure at 5 and at 50 ft c.; and (*b*) for the white test-object on black with the black

DATA FOR CURVES IN FIG. 3

J.N.D.	50 Foot-candles		5 Foot-candles	
	White on Black. Time of exposure (sec)	Black on White. Time of exposure (sec)	White on Black. Time of exposure (sec)	Black on White. Time of exposure (sec)
1	0.00145	0.00388	0.00251	0.00612
2	0.00155	0.00398	0.00273	0.00637
3	0.00165	0.00410	0.00297	0.00665
4	0.00175	0.00420	0.00320	0.00710
5	0.00187	0.00432	0.00340	0.00775
6	0.0020	0.00440	0.00362	0.00845
7	0.00210	0.00452	0.00387	0.00915
8	0.00220	0.00465	0.00410	0.00987
9	0.00230	0.00477	0.00430	0.01065
10	0.00240	0.00490	0.00452	0.01155
11	0.00251	0.00502	0.00477	0.01265
12	0.00262	0.00515	0.0050	0.01375
13	0.00273	0.00525	0.00520	0.01490
14	0.00285	0.00535	0.00540	0.01600
15	0.00297	0.00560	0.00575	0.01740
16	0.00310	0.00575	0.00610	0.01900
17	0.00320	0.00613	0.00655	0.02080
18	0.00330	0.00645	0.0070	0.0230
19	0.00340	0.00690	0.00745	0.0260
20	0.00350	0.00735	0.00775	0.0308
21	0.00362	0.00787	0.00840	0.0370
22	0.00375	0.00860	0.00935	0.0470
23	0.00387	0.00955	0.01030	
24	0.0040	0.01045	0.01140	
25	0.00410	0.01160	0.01270	
26	0.00420	0.01270	0.01480	
27	0.00430	0.01520	0.01680	
28	0.00440	0.0180	0.02160	
29	0.00452	0.0220	0.03020	
30	0.00465	0.02670	0.0450	
31	0.00477	0.03360		
32	0.00490	0.04630		
33	0.0050			
34	0.00510			
35	0.00530			
36	0.00550			
37	0.00575			
38	0.00600			
39	0.00637			
40	0.00675			
41	0.00725			
42	0.00775			
43	0.00840			
44	0.00935			
45	0.01105			
46	0.01330			
47	0.0220			
48	0.0340			
49	0.0523			

TABLE I

SHOWING THE EFFECT OF THE BRIGHTNESS OF THE PRE-EXPOSURE ON THE SPEED OF DISCRIMINATING BLACK LETTERS ON WHITE AND GRAY BACKGROUNDS AND WHITE LETTERS ON BLACK AND GRAY BACKGROUNDS AT 5 AND 50 FT C

Intensity of Illumination (ft c)	Test-object	Background	Pre-exposure	Time of Discrimination (sec)	Speed (Reciprocal of Time)
5	black	white	white	.007	142.9
			black	.0059	169.5
			gray	.0065	153.8
	white	black	white	.0117	85.5
			black	.005	200.0
			gray	.0073	137.0
	black	gray	white	.0468	21.4
			black	.0195	51.3
			gray	.0260	38.5
	white	gray	white	.0136	73.5
			black	.00651	153.6
			gray	.0078	128.2
50	black	white	white	.0041	243.9
			black	.0025	400.0
			gray	.0032	312.5
	white	black	white	.00612	163.4
			black	.00238	420.2
			gray	.00295	339.0
	black	gray	white	.0195	51.3
			black	.0052	192.3
			gray	.0112	89.3
	white	gray	white	.00675	148.2
			black	.00287	348.4
			gray	.00362	276.2

pre-exposure at 5 and at 50 ft c. These curves are given in Fig. 3.

The following conclusions may be drawn from these curves. (1) The threshold time of sensation for the black object on white with the white pre-exposure is considerably longer than that for the white object on black with the black pre-exposure as is shown in the following table:

Condition	Illumination (ft c)	Time of discrimination (sec)	Speed (reciprocal of time)
Black on white	50	.0038	258
White on black	50	.00145	690
Black on white	5	.00612	163
White on black	5	.00251	398

This may result from any or all of the following causes: greater strength of positive after-image of the white than the black pre-exposure; longer duration of the positive after-image of the white than the black pre-exposure; greater masking action of the white than the black positive after-image; less lag in the response to the white than the black test-object; and greater sensation difference between object and background in case of white on black than black on white.

(2) The white positive after-image in effect dies away more slowly than the black, *i.e.*, the rate of rise of the sensation aroused by the black object on white is slower when subjected to the influence of the white pre-exposure than that aroused by the white object on black when subjected to the influence of the black pre-exposure. At 50 ft c there is still an appreciable effect of the white after-image at .02 sec (reciprocal 50); the black after-image on the other hand is almost gone at .01 sec (reciprocal 100); at 5 ft c there is an appreciable effect of the white after-image at .03 sec (reciprocal 33) while the black after-image is almost gone at .02 sec (reciprocal 50).

(3) Under the conditions used there are more time just noticeable differences in the sensation aroused by the white object on black than in the sensation aroused by the black object on white. In fact the sensation from the black object on white at 50 ft c is only a few steps higher above the threshold than the sensation from the white object on black at 5 ft c.

(4) The number of just noticeable differences obtained with a given exposure-time and a given difference in cœfficient of reflection between object and background increases rapidly with increase of intensity of illumination, and this increase is more rapid for the white object on black than for the black object on white. This is shown in the following table for two exposure-times, .007 and .01 sec.

Condition	Illumination (ft c)	Exposure-time (sec)	Number of j.n.d's
Black on white	5	.007	4
	50	.007	19
White on black	5	.007	18
	50	.007	41
Black on white	5	.01	8
	50	.01	23
White on black	5	.01	22
	50	.01	44

Several points of comparison may be noted between the curves for the rise of sensation and the curves representing speed of vision.

(1) Even though the time necessary for discriminating the white letter on black after a black pre-exposure is shorter than for discriminating the black letter on white after a white pre-exposure, a higher sensation difference between letter and background is needed in the former than the latter case. This is shown in the following table:

Condition	Illumination (ft c)	Time of discrimination (sec)	Number of j.n.d's given in this time
Black on white	50	.0041	3
White on black	50	.00225	8–9
Black on white	5	.007	4
White on black	5	.0045	10

The sensation curves were determined only for the 3-min test-object. Similar comparisons may, however, be roughly made between the discrimination-time needed for the 1 and 2-min test-objects and the number of just noticeable steps aroused in these intervals, as shown in the sensation curves given in Fig. 3. In every case the sensation aroused by the white object on black must have risen to a higher value for the discrimination of detail than the sensation aroused by the black object on white.

(2) If the time needed for arousing the first trace of sensation be subtracted from the discrimination-time in any case,

a value will be given which will show the time needed for the discrimination of detail after the sensation is set up. These values for the black letter on white and the white letter on black at 5 and 50 ft c, are as follows:

Black on white at 5 ft c:	Threshold time of sensation	.00612 sec
	Discrimination-time	.007
	Difference	*.00088*
White on black at 5 ft c:	Threshold time of sensation	.00251
	Discrimination-time	.005
	Difference	*.00249*
Black on white at 50 ft c:	Threshold time of sensation	.00388
	Discrimination-time	.0041
	Difference	*.00022*
White on black at 50 ft c:	Threshold time of sensation	.00145
	Discrimination-time	.00225
	Difference	*.0008*

At both intensities, then, a longer time is needed after the sensation is set up to discriminate detail in white letters on black than in black letters on white. Further this difference in time for the two situations is relatively greater at high than at low illuminations. That is, at 5 ft c it takes approximately three times as long to discriminate detail in white letters on black after the sensation is set up, and at 50 ft c four times as long. It is possible that if the factor of pre-exposure could be eliminated or reduced in amount, speed like acuity would be higher for black letters on white than for white on black at all intensities of illumination and for all sizes of detail. On the other hand, it is also possible that even could this be done, the greater sensation difference which, our results indicate, is present between object and background in case of white on black, would be sufficient to cause a higher speed of seeing white on black than black on white.

(3) It was pointed out above that the curve representing the rise of the sensation aroused by the black test-object on white with the white pre-exposure at 50 ft c is only very little higher than that for the white test-object on black with the black pre-exposure at 5 ft c. It is interesting to note in this connection that the time necessary to discriminate the detail in the black letter at 50 ft c is .0041 sec (reciprocal 244) and the white letter at 5 ft c is .005 sec (reciprocal 200).

The bearing of these results on the problem of the relation of intensity of light to speed of vision would seem to be that our tests of speed of vision may underestimate the effect of the high intensities of illumination, particularly for large test-objects, and that this underestimation may be greater for black objects on white than for white objects on black. We feel, however, that the question is still an open one whether white on black or black on white is more quickly discriminated in the ordinary use of the eyes, in which case the eye dwells on the object viewed longer than is necessary. We are convinced that for any given size of detail, the sensation from such objects as a white letter on black (detail to be discriminated black) must be higher above the threshold to be discriminated than the sensation from a black letter on white (detail to be discriminated white); and that a longer time is necessary for this discrimination after the first trace of sensation is aroused. This is probably due to the fact that the effect of irradiation is the image formed on the retina is to decrease the size of detail for the white letter on black and to increase it for the black letter on white.

The Benefit of Increase of Intensity of Illumination at Various Points in the Intensity Scale

As a further aid in comparing the benefit of increase of intensity of illumination at various points in the intensity scale for black objects on light backgrounds and for white objects on dark backgrounds, curves have been plotted (Fig. 4) to show the percentage increase in speed for each increase of 5 ft c in illumination. Five foot-candles was chosen as the illumination at which to begin the computations of percentage change. The principle employed in making the determinations was similar to that which is used in computing the Fechner fraction, *i.e.*,

$$\text{Percentages} = \frac{(\text{Speed at 10 ft c} - \text{Speed at 5 ft c})}{(\text{Speed at 5 ft c})};$$

$$\frac{(\text{Speed at 15 ft c} - \text{Speed at 10 ft c})}{(\text{Speed at 10 ft c})}; \text{ etc.}$$

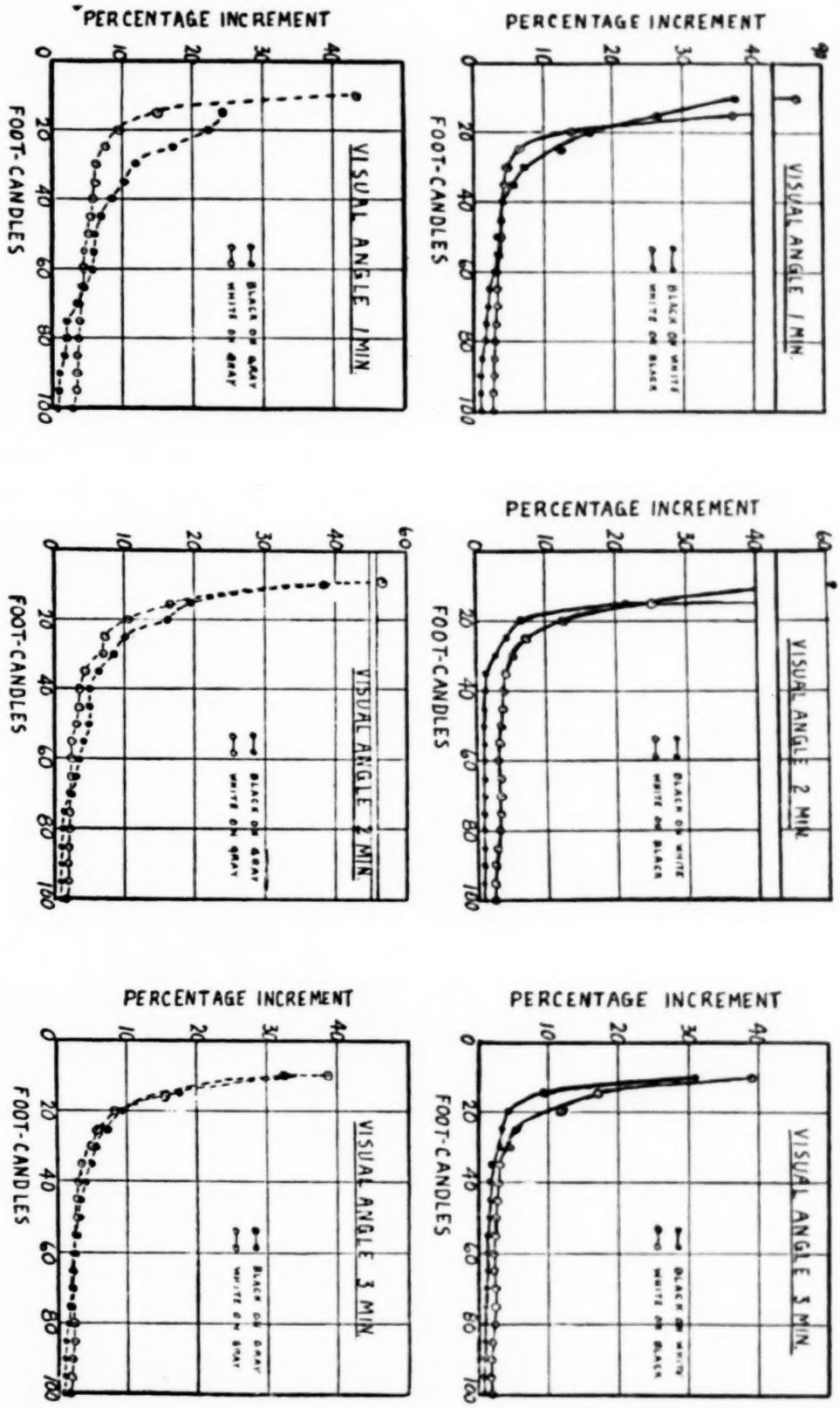


FIG. 4. Curves showing the percentage increase of speed for each increase of 5 ft c in illumination for each of the conditions tested. The upper row gives the comparison for white test-objects on black background and for black on white; the lower, for white and black test-objects on the gray background.

In Fig. 4 the upper row of charts shows the percentage change in speed for the black test-object on the white ground and the white test-object on the black ground for the three visual angles used for both conditions; and the lower row for the black and white test-objects on the gray ground. As before, the experimental points determined for the black test-objects are indicated by dots and for the white by circles; the curves for the white and black backgrounds, by solid lines and for the gray backgrounds by broken lines.

The percentage curves for the different conditions of work have the same general form. However, the knee of the curves for the white objects on black comes at more nearly the same intensity for all three visual angles than is the case for the white objects on the gray and for the black objects on both the gray and the white backgrounds. At the very high intensities the percentage increase in speed for each increment of 5 ft c in illumination is of the order of 1–2 percent for the

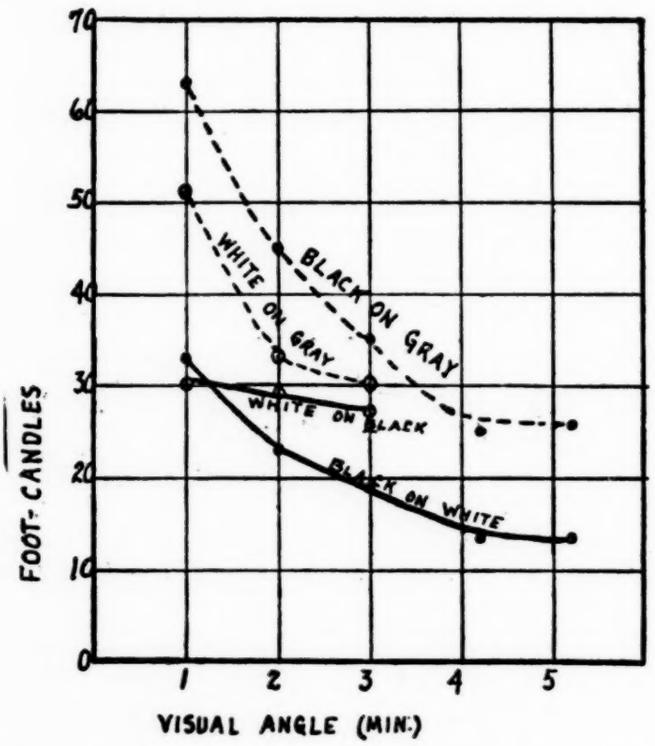


FIG. 5. Curves showing for each visual angle and each condition of object and background the illumination below which an increase of 5 ft c produces more than 5 percent, and above which an increase of 5 ft c produces less than 5 percent increase in speed of vision.

DATA FOR CURVES IN FIG. 6

Illumination (ft. c)	1 min Black on Gray		1 min White on Gray		3 min Black on Gray		3 min White on Gray		5 min Black on Gray	
	Time of discrim'n (sec)	Speed (Recip'al of time)	Time of discrim'n (sec)	Speed (Recip'al of time)	Time of discrim'n (sec)	Speed (Recip'al of time)	Time of discrim'n (sec)	Speed (Recip'al of time)	Time of discrim'n (sec)	Speed (Recip'al of time)
					Observer E. T. H.					
5	.....	.....	0.0705	14.2	0.0275	36.4	0.005625	177.7	0.010	100.0
10	0.107	9.3	0.0400	25.0	0.0120	83.3	0.0050	200.0	0.00760	131.6
20	0.071	14.0	0.0260	38.4	0.00875	114.3	0.004125	242.4	0.00555	180.2
30	0.055	18.1	0.0220	45.5	0.00750	133.3	0.003625	275.8	0.0050	200.0
50	0.045	22.2	0.0180	55.5	0.00650	153.8	0.003125	320.0	0.00450	222.2
80	0.034	29.4	0.0160	62.5	0.00625	160.0	0.002750	363.6	0.0040	250.0
					Observer C. H.					
5	.....	.....	0.066	15.1	0.0205	48.8	0.007125	140.3	0.0170	58.8
10	0.106	9.4	0.0384	26.0	0.0150	66.6	0.00550	181.8	0.0096	104.1
20	0.060	16.7	0.027	37.0	0.0110	90.0	0.004375	228.5	0.0065	153.8
30	0.044	22.7	0.022	45.5	0.0085	117.6	0.003811	262.3	0.00587	170.3
50	0.028	35.7	0.018	55.5	0.0075	133.3	0.003375	296.2	0.0050	200.0
80	0.020	50.0	0.0154	64.9	0.00712	140.0	0.002875	347.8	0.00463	215.9
					Observer J. F. F.					
5	.....	.....	0.1035	9.7	0.020	50.0	0.006875	145.5	0.0135	74.9
10	0.0102	9.8	0.040	25.0	0.155	64.5	0.00550	181.8	0.010	100.0
20	0.0645	15.5	0.018	55.5	0.0110	90.9	0.004125	242.4	0.00775	129.0
30	0.0425	23.5	0.0147	68.0	0.00875	114.2	0.003811	262.8	0.00650	153.8
50	0.034	29.4	0.0130	76.9	0.0070	142.8	0.003375	296.2	0.00560	177.9
80	0.0265	37.7	0.0122	81.9	0.00675	148.0	0.002875	347.7	0.0050	200.0

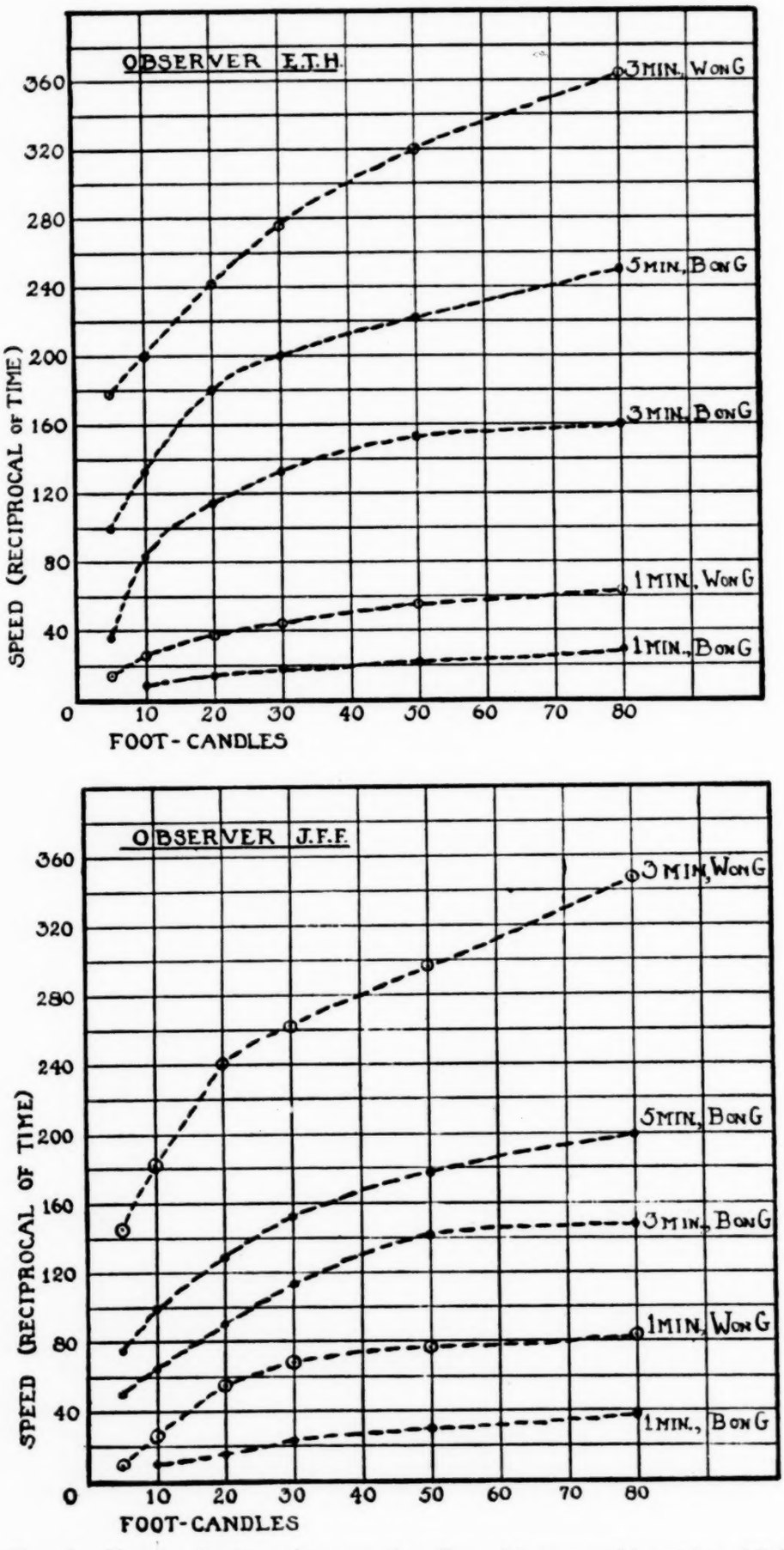
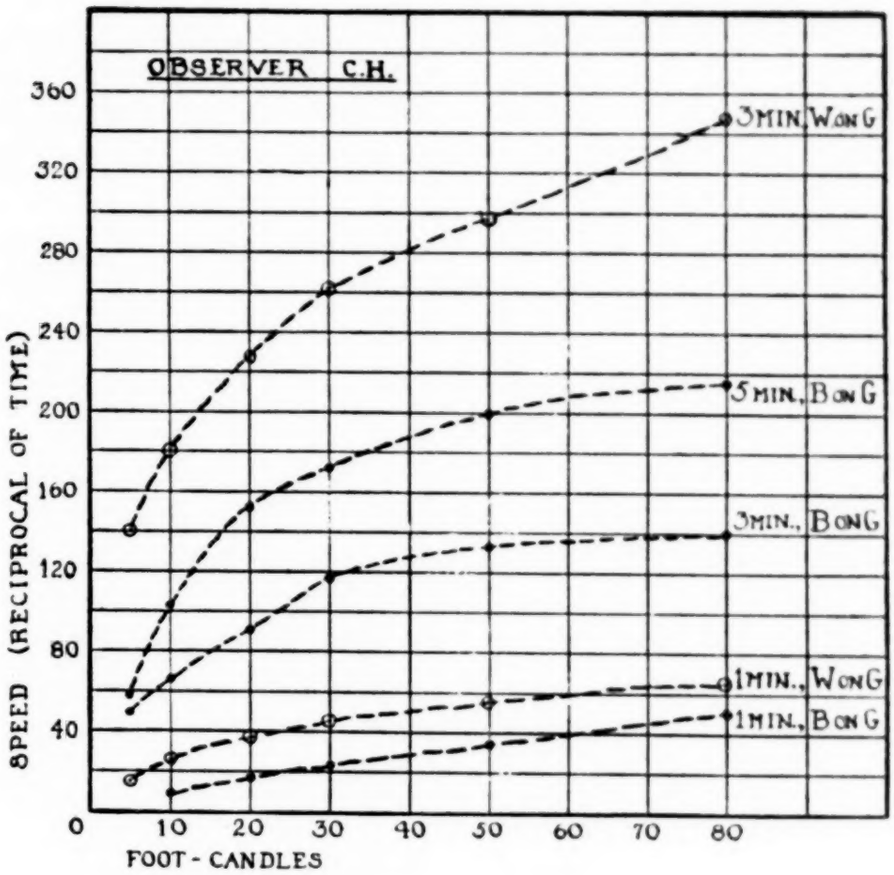
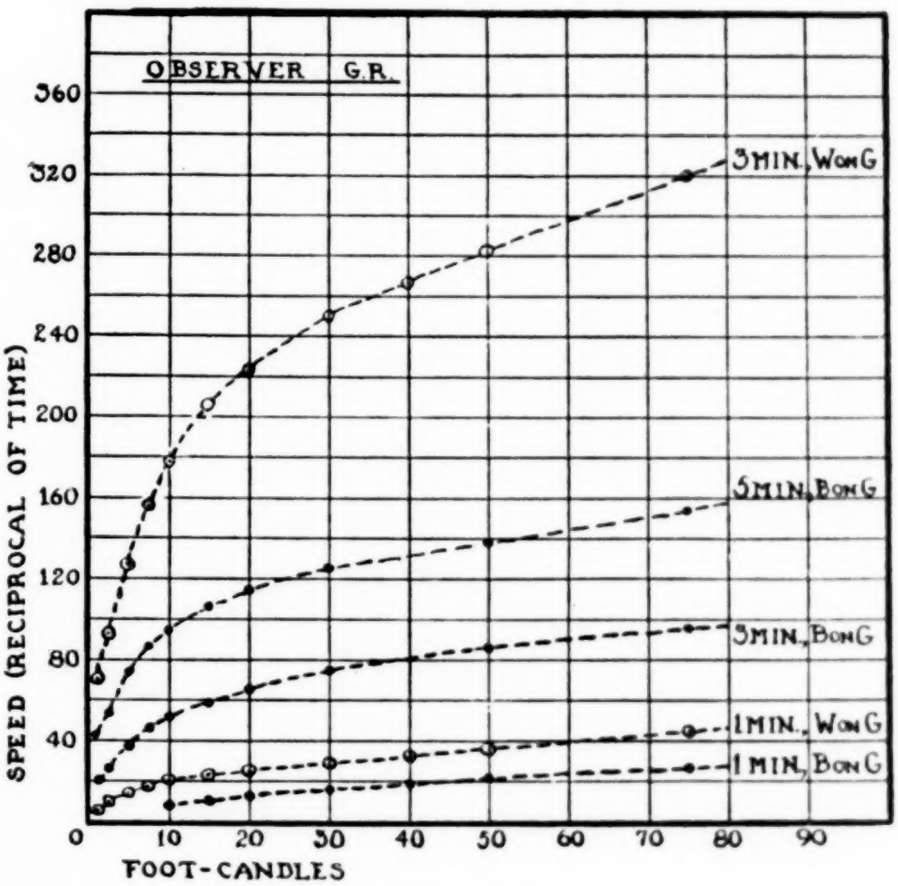

OBSERVER E.J.H.
3 MIN. W ON G
5 MIN. B ON G
3 MIN. B ON G
1 MIN. W ON G
1 MIN. B ON G
SPEED (RECIPROCAL OF TIME)
FOOT-CANDLES
OBSERVER J.F.F.
3 MIN. W ON G
5 MIN. B ON G
3 MIN. B ON G
1 MIN. W ON G
1 MIN. B ON G
SPEED (RECIPROCAL OF TIME)
FOOT-CANDLES

FIG. 6. Showing for four observers the effect of increase of intensity of light on speed of vision. Conditions tested,—1, 3 and 5 min black test-objects on gray back-





ground (21 percent coefficient of reflection) and 1 and 3 min white test-objects on the same gray background.

black test-objects on the white and gray backgrounds, and of the order of 2–4 percent for the white test-objects in the black and gray grounds.

As a further aid to the analysis of the effect of increase of intensity of illumination on the rate of increase in speed of vision, the curves shown in Fig. 5 have been plotted. In this figure are shown for each visual angle and each condition of test-object and background the illumination below which an increase of 5 ft c produces more than 5 percent increase in speed of vision, and above which an increase of 5 ft c produces less than 5 percent increase. The location of this critical illumination for all visual angles of the white test-object on the black background at nearly the same intensity (27–30 ft c) is brought out clearly. For the smaller visual angles the knee of the curve occurs at a lower intensity for white on black than for black on white; for the larger visual angles, at a lower intensity for black on white than for white on black.

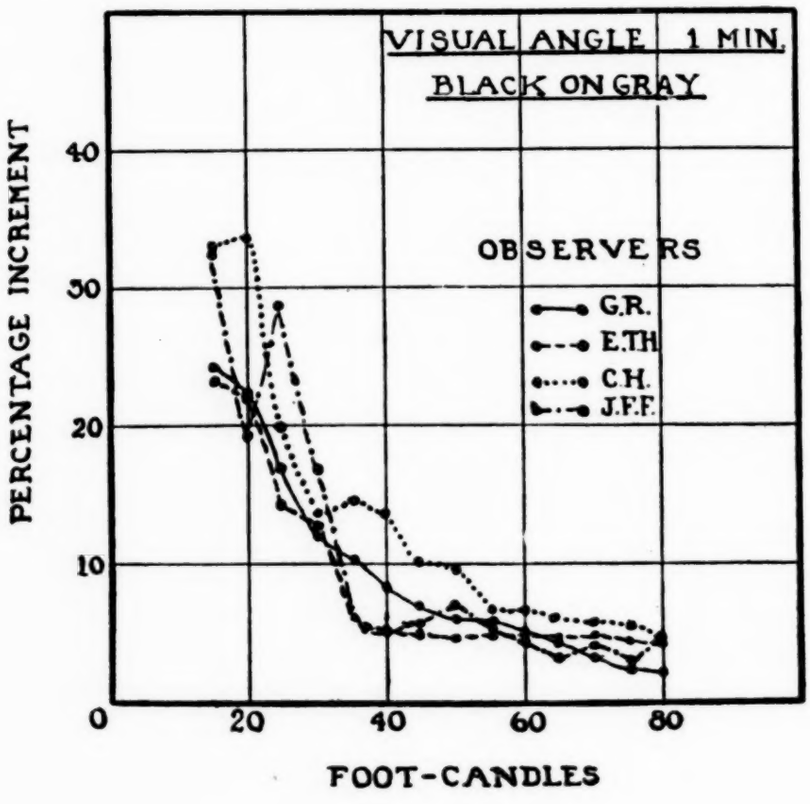


FIG. 7.

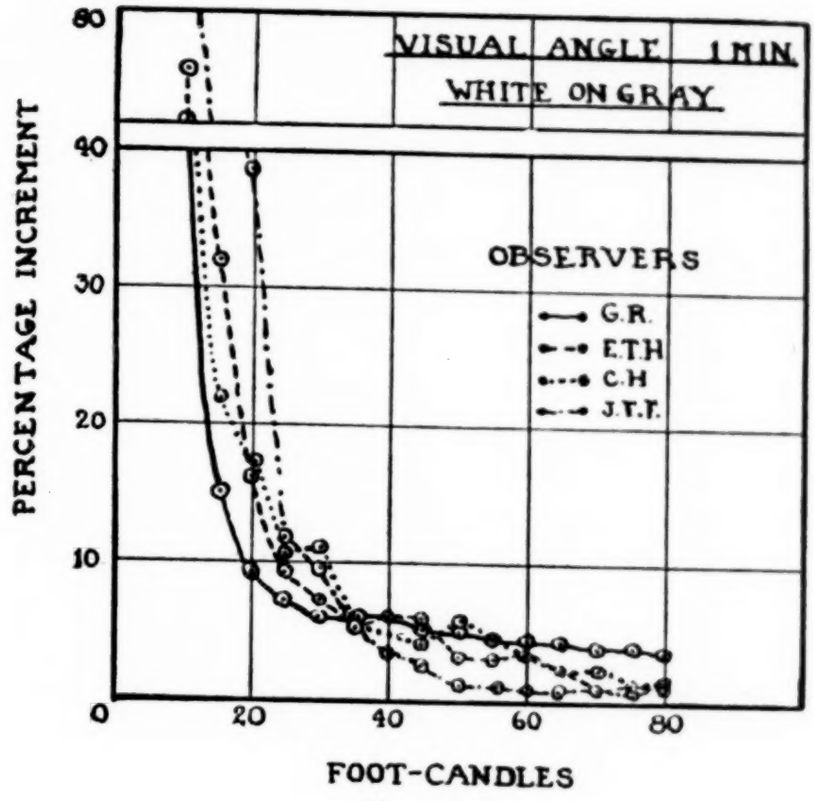

VISUAL ANGLE 1 MIN.
WHITE ON GRAY
OBSERVERS
G.R.
E.T.H.
C.H.
J.T.F.
PERCENTAGE INCREMENT
FOOT-CANDLES
0
10
20
30
40
60
80

FIG. 7.

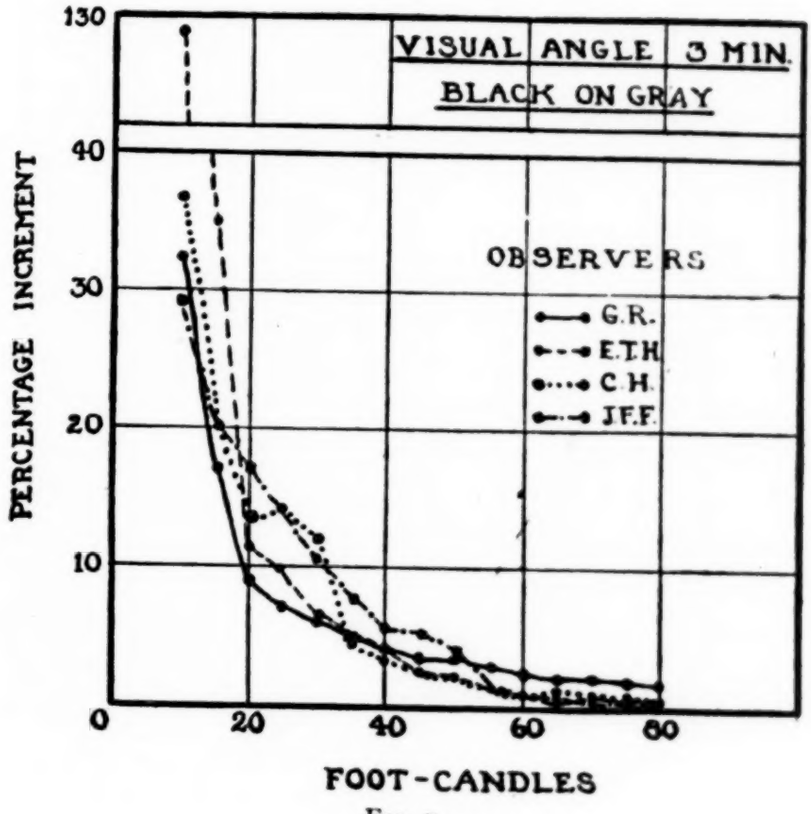

VISUAL ANGLE 3 MIN.
BLACK ON GRAY
OBSERVERS
G.R.
E.T.H.
C.H.
J.F.F.
PERCENTAGE INCREMENT
FOOT-CANDLES
0
10
20
30
40
60
80
130

FIG. 7.

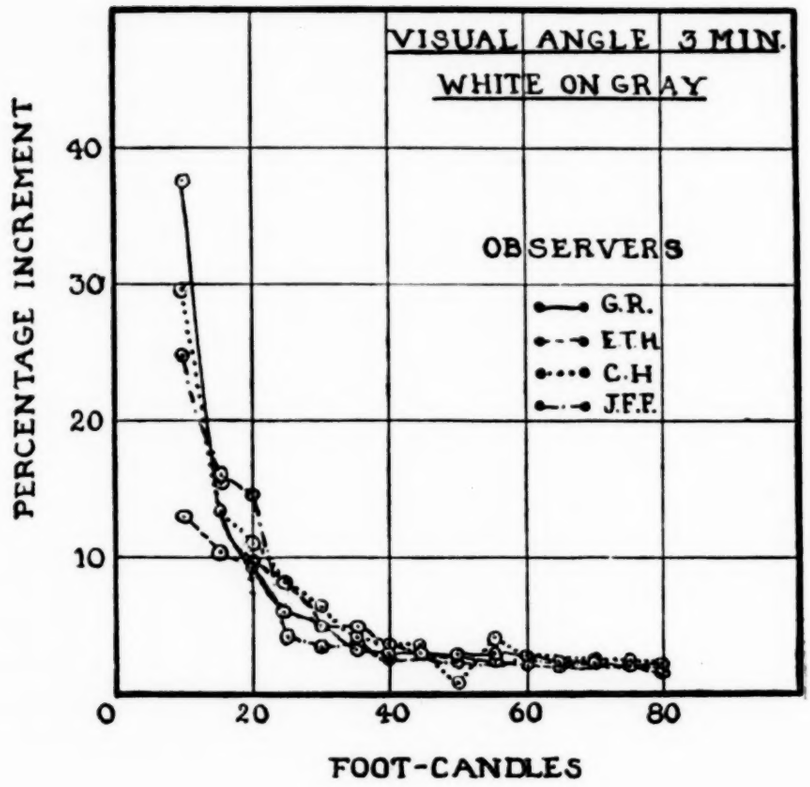


FIG. 7.

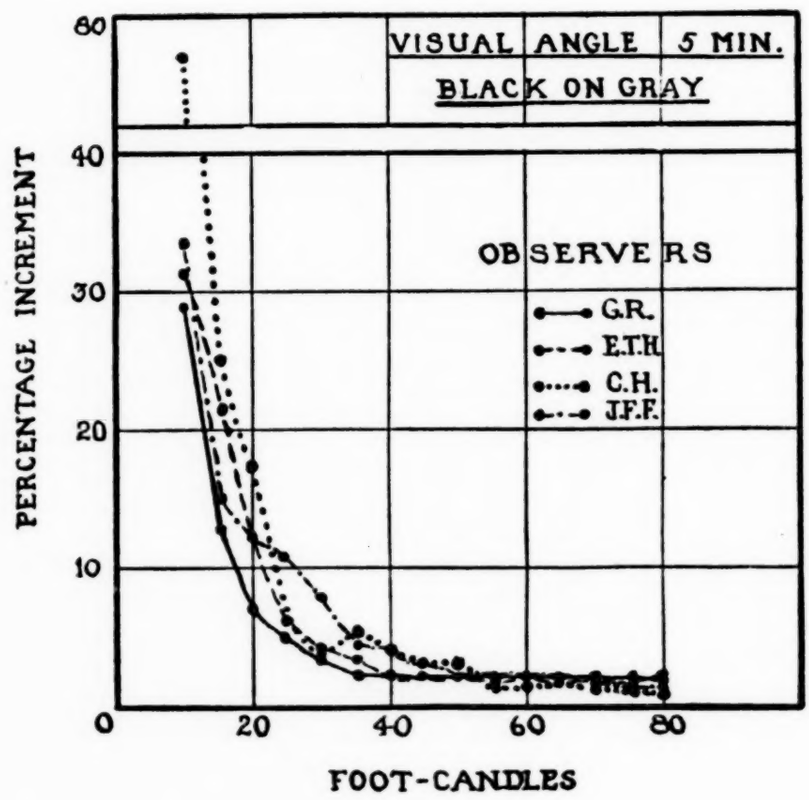


FIG. 7.

FIG. 7. Curves for the four observers showing the percentage increase in speed for each increase of 5 ft c in illumination. Conditions tested same as for Fig. 6.

Individual Differences in the Effect of Increase of Intensity of Light on Speed of Vision

In order to ascertain how the results obtained by Observer R on the effect of increase of intensity of light on speed of vision for dark objects on light and light objects on dark backgrounds, compare with results for other observers, certain sections of the work were repeated with three new observers.[1] The test-room, conditions of work, distance of observer, etc. were the same as were used by Observer R. The three observers were emmetropes, 22 years of age. A long period of training was found to be necessary to give them the practice and precision needed for making consistent judgments.

Speed of discrimination was determined for these observers for illuminations ranging from 5 to 80 ft c, using 1, 3 and 5 min black test-objects on a gray background having 21 percent cœfficient of reflection, and 1 and 3 min white test-objects on a gray background of the same cœfficient of reflection. These relations of object and background were selected because they were considered more significant for industrial situations than black on white and white on black.

The results are given in Figs. 6 and 7. Fig. 6 shows the curves for the three new observers and for Observer R, all plotted to the same scale. These results show that although, as would be expected, the actual speeds vary for the different observers,—being higher for the younger, emmetropic observers than for Observer R who is a corrected myope,—the more significant features of the curves are the same for all. These features are (1) the higher speeds obtained for large than small test-objects; (2) the higher speeds obtained for white than black test-objects on the gray background; (3) the higher speed obtained for a 3-min white test-object on gray than for a 5-min black test-object on gray; (4) the sharper initial rise and more pronounced knee to the curves for the larger than the smaller test-objests; (5) the location of the knee of the curves at the lower intensities when the larger test-objects are used; and (6) the general similarity of shape of curve for all observers.

[1] These data were obtained by Clare Hardy and Edith Harris of Bryn Mawr College, working under the direction of the writers.

The last of the above points is demonstrated more clearly perhaps in Fig. 7 which shows the percentage increase in speed for each increase of 5 ft c in illumination. In this figure charts are given on which are plotted the results for all four observers for each test condition. There is a remarkably close agreement between the curves, which indicates that the percentage benefit of increase of intensity at various points in the intensity scale is of the same order of magnitude for this group of observers. The location of the critical illumination, *i.e.*, the illumination below which an increase of 5 ft c in illumination produces more than 5 percent increase in speed and above which, less than 5 percent increase in speed, is over a very small range in the intensity scale for the four observers. This range can be readily seen in the charts by the scatter of results along the horizontal co-ordinate at the 5 per cent level.

Conclusions

(1) With the exception of amount, the effect of increase of intensity of light on the speed of discriminating light objects on dark backgrounds is in general similar to that previously found for dark objects on light backgrounds. That is, the large effects of increase of intensity occur in the lower part of the intensity scale, and the speed of discrimination is higher for large than small visual angles and for large than small differences in coefficient of reflection between object and background. The curves for the light test-objects on dark backgrounds are, however, on the whole higher, steeper and less flattened at the high intensities than those for the dark test-objects on light backgrounds.

(2) The amount of effect is greater for light objects on dark backgrounds than for dark objects on light backgrounds. Two reasons may be offered for this. (*a*) With a given difference in coefficient of reflection between object and background, the visual or sensation difference increases rapidly with increase of intensity of illumination. This obviously is a very important factor in the increased visibility of objects produced by increasing the intensity of illumination.[1] This increase

[1] Whether there is also an increase in the spatial aspect, *i.e.*, the apparent size of the object, has, so far as we know, not been definitely or directly determined.

is more rapid for light objects on dark backgrounds than for dark objects on light backgrounds. And (*b*) there is probably less increase of the inhibitive action of the pre-exposure with increase of intensity of illumination for light objects on dark backgrounds than for dark objects on light backgrounds.

(3) Near the threshold of acuity, *i.e.*, for small visual angles and low intensities, speed of discrimination is higher for such objects as a black letter on white (detail to be discriminated white) than for a white letter on black (detail to be discriminated black). At this level of seeing, space discrimination is probably the most important factor in the speed of discrimination of detail. Because of irradiation in the image formed on the retina, the detail to be discriminated in case of the black letter on white is larger than that to be discriminated in case of the white letter on black.

(4) At the higher levels of sensation speed of discrimination is higher for white objects on black than for black on white, and for white than black objects on a gray ground of approximately the brightness of unpolished steel (21 percent cœfficient of reflection). The explanation of these results brings out two factors in speed of vision the importance of which has not been fully recognized: (*a*) the effect of physiological induction or contrast on the difference in sensation between object and background in different relations of object to background; and (*b*) the effect of type of pre-exposure on the difference in sensation between object and background due to the persistence of sensation or the positive after-image. The influence of the first of these factors is to cause a greater increase in this difference in case of a white object on a black ground and therefore a greater increase in the speed of discrimination. In case of the second of these factors, the greater difference in sensation between object and background and therefore the greater speed of discrimination occurs with a black pre-exposure and a white object on a black background. In case of the gray background, an additional cause of the result is the fact that the gray used is nearer to the black than to the white test-letter in sensation value.

(5) The knee of the curves for the white test-objects on black comes at more nearly the same intensity for the three visual angles used than is the case for the white test-objects on the gray and for the black test-objects on both the gray and the white backgrounds. For the smaller visual angles the knee occurs at a lower intensity for the white test-object on black than for the black test-object on white, and for the larger visual angles the converse of this is true. The curves for the black test-objects on the white and gray backgrounds are more flattened at the very high intensities than for the white test-objects on black and gray. That is, at these intensities the percentage increase in speed for each increment of 5 ft c in illumination is of the order of 1–2 percent for the black test-objects and of the order of 2–4 percent for the white test-objects.

(6) The question whether the power of discriminating light objects on dark backgrounds is greater than that of discriminating dark objects on light backgrounds in the ordinary use of the eyes probably can not be settled by investigations of the type conducted here. It is not known, for example, how much of the effect of the pre-exposure is present in the ordinary act of seeing, in which case the eye dwells on the object viewed longer than is necessary. Our results show, however, that for any given size of detail, the sensation from such objects as a white letter on black (detail to be discriminated black) must be higher above the threshold to be discriminated than the sensation from a black letter on white (detail to be discriminated white); and that a longer time is necessary for this discrimination after the first trace of sensation is aroused. This is probably due to the fact that the effect of irradiation in the image formed on the retina is to decrease the size of detail for the white letter on black and to increase it for the black letter on white.

(7) The following factors tend to render black test-objects on white less quickly discriminable than white on black: (*a*) the smaller difference in sensation between object and background due to the effect of physiological induction or contrast; and (*b*) the greater amount this difference may be obscured by

the positive after-image following the pre-exposure which usually occurs with this relation of object to background. The factors on the other hand which tend to render white test-objects on a black background less quickly discriminable than black on white are: (*a*) the smaller detail to be discriminated due to irradiation in the image formed on the retina; (*b*) the greater difference in sensation between object and background that is required for discrimination; and (*c*) the longer time that is necessary for discrimination after the first trace of sensation is aroused. The relative values of speed in any particular comparison will depend upon the interplay of these factors.

(8) Curves representing the effect of increase of intensity of light on speed of discriminating white and black test-objects on gray obtained for four observers, show that the results of Observer R, who had been used throughout the series of experiments, are typical in their important features. These features include the comparative shape and height of the curves for the black and white objects on gray and the percentage benefit of increase at various points in the intensity scale.

(9) With reference to the comparative effects of size, relation to background, and intensity of illumination on the visibility of objects, speed taken as the reciprocal of the time threshold is shown to be a sensitive measure of visibility. The direct measure in any instance would be, of course, in terms of the number of just noticeable differences in visibility. The judgment required, however, would be difficult to make and the procedure in making the determinations so time-consuming as to be somewhat infeasible for any great number of conditions or situations in which a factor may be operative. The correctness of speed as a measure, if visibility is to be conceived as that obtained with the optimum time of exposure, is vitiated by the selective effect of the factors in question on the rate of rise of sensation. Considered in relation to its practical bearings, however, speed is a very important aspect of seeing and of visibility. Also in case of the present study it has the advantage of being completely outside the group

whose effects are to be compared; *i.e.*, within the group the effect of any two could be compared in terms of the effect on the third, but the effect of the third could not enter into the comparison.

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FACTORS WHICH INDIRECTLY AFFECT PAROTID SECRETION[1]

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In earlier reports those factors were considered which appear to affect the quantity of parotid secretion directly (12, 13). It is the purpose of this communication to present data showing variation in secretion as a result of what might be interpreted as more complex and indirect influences. The application of the conditioned reflex technique of Pavlov to human subjects awaits a better understanding of the complex nature of these organic factors. Before the effect of these influences could be determined, however, the rate of secretion in the absence of extero-stimulation had to be investigated. Previous investigators disagree as to the constancy of the secretion of these glands when indirect stimulation alone is operative.

Very few studies have been concerned with this problem. Mischerlich (9), Zebrowski (16), and Brunacci (1) observed subjects with abnormal fistulas and reported that there was no secretion when the subject was resting. Krasnogorski (5) later called attention to the fact that secretion from such fistulas caused by severe burns or cuts in childhood is not a reliable index of parotid secretion. In a subject he studied who was afflicted with such a fistula, it was noted that the normal side to which a disc was attached always secreted more than the abnormal side. Lashley (8) found, and we have verified his findings, that the disc itself is not an excitatory factor. He also computed the rate of secretion under conditions of as little stimulation as possible. The subject remained quiet with mouth closed, but without inhibiting the swallowing reflex or movements adjusting the position of the body. Al-

[1] The investigation upon which this article is based was supported by a grant from the Heckscher Foundation for the Advancement of Research established by August Heckscher at Cornell University.

though marked extra organic stimulation was lacking the glands appeared to be subject to almost constant stimulation from some source and the secretion continued to flow. In our own investigation the secretion from one gland for one hour was checked. When the subject sat quietly at a desk breathing through the nostrils and not inhibiting the swallowing reflex the secretion for that hour was 4.80 cc. When the same subject reclined on a couch for a similar length of time the flow was reduced to .80 cc. In every test we made we found a continuous though variable secretion so long as there was sufficient fluid in the organism to prevent excessive thirst, and no inhibitory stimulation existed. This effect of liquid in the organism appears to be very important. Apparently it has been overlooked by investigators of parotid secretion. Its influence on the quantity of saliva secreted under both direct and indirect stimulation is shown in the following experiments.

When one subject abstained from the ingestion of liquids of any kind over a period of thirty-six hours, the effect of the reduction of water in the system was very noticeable. Chewing a tasteless gum between the second molars on the side from which the saliva was being drained caused 4.30 cc of saliva during a five-minute test, 18 hours after the last liquid had been taken. The same process of chewing (to the beat of a metronome) 6 hours later yielded 2.90 cc and the subject reported his mouth to be getting dry. A similar check 13 hours later yielded 1.10 cc and the subject's mouth was very dry. He was so thirsty that he was unable to sleep well the latter part of the second night. After the last test reported above the subject drank two pints of water. Fifteen minutes later the five-minute chewing stimulation again yielded 2.25 cc and one hour later, after a breakfast consisting of cereal and cream, the flow was again back to 4.25 cc.

During the 36 hour thirst period, tests of the flow of secretion for a five-minute period in which there was no direct chewing stimulation was also taken at intervals. The drop was from .14 cc in the beginning of the experiment to .01 cc during the five-minute period immediately preceding the drinking of water. Swallowing was inhibited during these

tests, but one swallow per minute was allowed during the chewing. These data suggest a close relationship between the quantity of salivary secretion and dehydration in the organism. Further data suggesting the value of salivary tests in determining the condition of dehydration will be presented in a later paper. The amount of fluid in the system expressed in the condition of thirst of the subject must be taken into account as an indirect factor affecting parotid secretion while the drying of the mucosa appears to be a direct influence of significance. Both of these factors are readily controlled in experiments involving other indirect factors. Incidentally these results may explain what has previously been interpreted as the influence of food in the stomach. It has probably been the influence of liquids in the food, rather than the food itself, since we found when the subject ate dry toast or soda crackers there was no increase in secretion from its being in the stomach. It might also account for the increase we were unable to explain when the subject remained lying in a warm bath or was taking physical exercise both of which increased the circulation of blood.

Apparently very few observations of the effect of 'mental' activity on secretion have been made. Brunacci and De-Sanctis (2) noted a smaller quantity of saliva during such activity than during repose. Lashley (8) questioned their technique and conducted an experiment requiring the subject to square three-place numbers without visual assistance for 20 minutes; to remain quiet for 20 minutes; and then to resume computation for 20 minutes. The average number of drops of secretion for the three periods was as follows:

1. Period of multiplication	1.80	drops per min
2. Period of rest	1.23	" " "
3. Period of multiplication	1.88	" " "

An increase in secretion for the period of 'mental' application is evident. Lashley reports one case where the secretion was decreased during the 'mental' activity but as this subject used his fingers in computation Lashley suggests a possible correlation between the 'implicit system employed and the affect of mental work upon secretion.'

Since these studies gave opposite results we arranged a series of tests involving what is ordinarily considered as 'mental' activity. The subject for these tests was a twelve-year-old boy who had been serving as a subject for salivary experiments for five months and was paid for his time. He was accustomed to the apparatus and laboratory situation but knew nothing of what it was all about. Records had been kept of both the secretory and motor aspects of his food responses and factors affecting parotid secretion in his case were quite well known. The experiments were conducted in a partially soundproof room at 4 P.M. each day. The boy was told to eat nothing after his lunch at 12 M. but was always given a drink of water before the test began to eliminate the thirst factor. Lashley's disc was used to collect the saliva and a modification of Richter's (11) device served as a means of measuring it.

After determining the control flow for two minutes, the subject was given a mechanical puzzle that he had never seen before and about which he appeared to be very curious. He was instructed to take it apart. He immediately went to work with what an ordinary observer would interpret as keen interest. At the end of two minutes the unsolved puzzle was taken away while he sat quietly for another two-minute period. The secretion from his right parotid gland during the three periods was as follows:

During the control period	.16 cc per 2 min
Working on the puzzle	.04 cc per 2 min
During the 2d control period	.17 cc per 2 min

This puzzle and others of a different type were presented at intervals as above and as long as the puzzle remained unsolved there was a reduction in secretion during the period in which he was working on it. After the puzzle was solved he was instructed to take it apart and put it together as rapidly as possible until told to quit. The results with the same puzzle used above were as follows:

During the control period	.17 cc per 2 min
Working on the solved puzzle	.19 cc per 2 min
During the 2d control period	.16 cc per 2 min

In another experiment the fundamental processes of arith-

metic as prepared on Courtis practice sheets were used to provide the 'mental' effort. The boy was urged to work rapidly and promised a bonus of one penny for each problem correctly solved. He intimated before the test began that he liked to do arithmetic. The problems for the period given below consisted of column addition of 3 columns of 9 digits each. He attempted 6 such problems and all but one were correct. The parotid secretion during the process was as follows:

During the control period	.20 cc per 2 min
Working the addition problems	.00 cc per 2 min
During the 2d control period	.22 cc per 2 min

On the following day a long series of column addition problems was provided and the subject was instructed to continue to work them until told to stop. The following amounts were collected during successive 2 minute periods:

During the control period	.11 cc no problems
Working the addition problems	.01 cc problems right 5
Working the addition problems	.04 cc problems right 4
Working the addition problems	.06 cc problems right 3
Working the addition problems	.08 cc problems right 3
Working the addition problems	.08 cc problems right 2

As the work proceeded the boy appeared to lose interest as the number of problems solved would indicate and at the end of the sixth continuous period he said "I would rather not do any more arithmetic now," He was then allowed to quit.

The results of these experiments are challenging. The data suggest a relationship of some sort between the activity engaged in and parotid secretion. Either the ordinary sources of stimulation for the normal flow were not operating or the glands were being inhibited directly or indirectly. During the period of the most intense activity, measured either by the appearance of the subject or the amount and accuracy of his performance, this influence was greatest. The effect appeared to change as the subject became less efficient, or less absorbed, or gave less attention, or became more fatigued, or as a result of a combination of these factors. Our opinion is that we have here an example of central inhibition. Evidence in justification of this interpretation will be postponed until after presentation of related data.

In spite of the fact that there is no anatomical or physiological basis for the assumption of direct 'voluntary' control of the parotid glands, there is a common notion that the mouth 'waters' when food is mentioned. The very meagre literature on the subject is not in agreement with this idea, but competent observers insist that it is well founded. After observing a healthy young woman with a parotid fistula of long standing, Stoney (12) reported that 'thinking of food' had considerable effect in one experiment but in others none at all. Gley and Mendellsohn (4) experimenting with a subject who had a similar fistula observed some secretion at the sight of food but no significant secretion 'at the thought' of it. Lashley (7) reported that there was no evidence of a conditioned salivary response at the mention of food. His account of his test follows.

"Early in my own experiments it became evident that no increase in secretion followed the mention of food. As it seemed possible that lack of real hunger was responsible for the absence of secretion, the first test for the conditioned reflex was made under rather severe conditions. The subject abstained from food for three days, the drainage tube was then placed over the left Stenson's duct, and a list of fifty-three words, fifteen of which were names of food, the others indifferent, was read to him. The words were given at two-minute intervals and the secretion recorded in drops per minute. The average secretion following the names of foods was 2.00 drops per minute; following the indifferent words it was 2.10 drops per minute. There is absolutely no evidence of a conditioned reflex."

It appears from these accounts that the mention of food under the conditions of these experiments has not been an effective stimulus for parotid secretion. Early in our study of the factors which indirectly evoke parotid secretion, we repeated Lashley's experiment and our results supported his conclusions—that is, the mere mention of names of food under the conditions which obtained at that time in the laboratory did not evoke a salivary response in the subjects used. One should not infer that the mention of names of food might not

become a signal for secretion in any normal individual or that it might not already be a stimulus for some. Salivation to any such indirect influence as a name spoken by some other person represents an individually acquired or conditioned stimulus and there would seem to be no reason to assume that any person would respond to the mention of food unless he had had the peculiar experience of always hearing the name of food mentioned just prior to its ingestion, any more than one would expect a dog to salivate at the sound of a metronome until that sound had preceded his eating on several occasions. On the other hand the repetition of any signal even though it becomes an effective stimulus as a part of one situation is not a guarantee that it will always be effective irregardless of other factors in the situation. Even a dog can detect the difference of the fraction of a tone between two situations, so that man could hardly be expected to respond to the mention of a name without some regard to the conditions under which the name was mentioned. Disregard of this factor may account for the lack of success which has attended most attempts to condition salivary responses in man, or to find evidence of such relationships. It seems from the literature having to do with the conditioning of human salivary responses that favorable results have been contingent upon the extent to which the total situation has been considered.

Brunacci (1) obtained no evidence of conditioned salivary responses in man. Zebrowski (16) noted occasional increases when his subjects saw food being brought to them. Gley and Mendellsohn (4) who were the first to attempt to create an artificial conditioned response of this type in human subjects, report a slight secretion at the sight of food, but their attempt to create a conditioned response to an electric light or a bell failed. They gave 40 joint stimulations of sound or light with the ingestion of food and suggest that perhaps the experiment was not continued long enough to be conclusive. Ordinarily the dog becomes conditioned with from 3 to 20 joint stimulations so that one might expect the human to make the association in 40 trials as far as exercise alone is concerned. Lashley (8) observed an increased secretion when his subject was

permitted to hold chocolate candy in the hand and a further definite increase when the subject brought the food nearer the mouth. Richter and Wadi (11) admit that the response has been successfully conditioned by Pavlov in dogs but "no one has been successful in conditioning these responses in human being" . . . "We, too, were unable to demonstrate any conditioned reaction."

From a report given before the Congress of Russian Physiologists in 1926 by Krasnogorski (6) it is evident that he had established both motor and secretory conditioned responses in children. His tables show increased responses to previously indifferent stimuli, such as a bell, electric light, and metronome. The significance of this report is the evidence it conveys that it is possible under proper direction to condition the parotid gland to artificial stimuli. We therefore determined to find out if possible what other indirect influences beside the mere reception of the impulse were at work in this process. So many failures would seem to indicate that still other indirect factors aside from those already reported need to be controlled before conditioning in the laboratory could be successful.

Our first attempt[1] was made without regard to the consistency of the situation to the subject. We proceeded, as others had done, under the assumption that proper sequence of stimulation, the indifferent slightly preceding the unconditioned, was the only essential technique for the development of conditioned salivary responses. We were able to get a strong direct secretion to acid in the mouth and paid no attention to the subject's interest in or attitude toward the process. The subject knew what it was all about and was apathetic as far as the acid was concerned. The method of presenting the joint stimulation was similar to that employed by Pavlov (10). The subject, a male adult, sat at a table in a partially soundproof experimental room and an electric bell was sounded a few seconds before orange juice was squirted into his mouth through a small tube connected with a gauge pump in the

[1] We wish to acknowledge the coöperation of Professor T. L. Bayne, Jr., in this experiment.

experimenter's chamber. The subject was instructed to hold the 2 cc of juice in his mouth for about five seconds and then swallow it. This joint stimulus, bell plus the orange juice, was distributed at varying intervals of from three to seven minutes' duration and about twenty such combinations were given each day. The quantity of saliva secreted by one parotid gland for each unconditioned stimulation amounted to about .75 cc in thirty seconds and it was recorded by the experimenter each thirty seconds. As the experiment progressed occasional tests for conditioning were made, that is, the bell would be sounded and no orange juice would be given. These tests yielded only intermittent evidence of conditioning although hundreds of combinations of the joint stimulation had been made during a period of several weeks. The results from this investigation supported those reported above in suggesting that other factors than those under control were preventing the development of a conditioned response. Undoubtedly the subject learned that he would receive orange juice after the bell with a few trials but there was no dependable anticipatory salivary flow.

In another experiment the subject, a twelve-year-old boy, was blindfolded. Food was placed in his mouth after the bell was sounded by opening his mouth and placing the food inside. He was told nothing. After the third trial he invariably opened his mouth for the food when the bell was sounded, but the secretion which was also checked gave only spasmodic evidence of a positive conditioned stimulus. Later this same subject was trained to open his mouth for food at a metronome beat of fifty beats per minute and never to open it at one hundred fifty beats per minute, but no such discrimination was noted so far as the saliva was concerned. There appears to be a difference in the facility with which motor and secretory conditioned food responses develop in human subjects. The latter appear to be influenced by factors not yet determined.

Assuming that the artificiality of the situation might be a disturbing factor in the development of these conditioned responses, our next attempt was carried out in a more natural eating situation. I made arrangements to eat my lunch each

day with a suction disc attached in order that I might observe variations in secretion under all conditions. After a few weeks of this practice I noted that whenever I sat at the eating table with the intention of eating, almost any stimulation that had previously preceded the actual ingestion of food might act as a natural conditioned stimulus. The sight of food, taking a spoon in the right hand, taking a sandwich in the right hand, or any other such sensory activity might cause a pronounced increase in the flow of saliva. If, however, the food was held in the hand without eating it, 'experimental extinction,' or 'inhibition,' according to Pavlov's theories, began at once. The organism began its process of adaption immediately by inhibiting a response to a false signal. An example of such an adjustment is shown in the changing quantities of saliva during successive minutes.

1.	Control flow for one minute	.08
2.	Food in the hand for one minute	.28
3.	Food remains in the hand	.20
4.	" " " " "	.16
5.	" " " " "	.18
6.	" " " " "	.10
7.	" " " " "	.06

These results were obtained accidentally. I had intended to eat the food but upon noticing the unusual increase in saliva as I raised it to my mouth, I became interested in seeing what would happen if I merely held the food without eating it. The response was extinguished in five minutes. The implications of this process for theories of learning were suggested in a former report (15).

During these experiences of eating my lunch in the laboratory another incident occurred which is of interest here. Just as I was preparing to eat my sandwich two ladies strayed into the laboratory door which had been inadvertently left unlocked. My unpresentable appearance caused me some embarrassment, but I continued to hold the food in my hand as I answered their queries. The record of the quantity of secretion for the five minutes preceding, during and following the ladies entrance is as follows:

1.	Five minutes before the disturbance	.72 cc
2.	Five minutes during the ladies visit	.03 cc
3.	Five minutes after their exit	1.20 cc

This record is the more remarkable when it is recalled that talking or any other mouth movement is ordinarily a direct excitatory factor.

This evidence of inhibition of secretion to what might be interpreted as a mild emotional state suggested a possible explanation of the difficulties noted above. If such slight organic changes could influence so effectively the ordinary flow of saliva it seemed probable that organic states might be blamed for failure to develop conditioned salivary responses. It was a simple matter to check such an hypothesis.

The procedure adopted was to determine first the normal rate of secretion for the subject at the time by recording the flow for each successive one half minute for several minutes, and then introduce various changes in the situation that might be said to create an affective state in the subject. The first test was with an electric shock. After checking the control flow for two minutes the subject, the same boy as before, was allowed to observe the experimenter attach electrodes connected with a series of dry cells to the boy's arm. The experimenter then announced that he would turn on the switch on the tenth bell. The bell was sounded each twelve seconds, so that there was a two-minute interval after the announcement before the boy was to receive the shock. No shock was given but what would seem to be the effect of the two minutes of anticipation is shown in the following record:

1. During the 2 minute control . . . . . .18 cc
2. During the 2 minutes of anticipation . . . . . .03 cc
3. During the 2 minutes after the bell . . . . . .15 cc

During the anticipatory period the boy gave every evidence of being afraid. He probably expected a more severe shock than it would have been possible for him to receive with the set-up as it was. The actual administering of the shock later had very little influence on the secretion. The definite inhibitory effect of this experience provided support to our hypothesis and many other such tests followed. In some of these tests distasteful food was used to see what effect anticipation of it would have on the secretion. The subject was

informed that on the tenth bell he would receive a spoonful of soda. The result was as follows:

1. During the 2 minute control period..... .23 cc
2. During the 2 minutes of anticipation..... .07 cc
3. A pinch of soda on the tongue for 2 minutes..... 1.52 cc

It was apparent that the viscosity of the secretion was materially changed during the second and third periods although no qualitative analysis was made. The material reduction in the quantity of the saliva suggests again an inhibitory influence although the boy was shuddering and protesting the dosage.

On another occasion a mixture of distasteful substances with epsom salts as a base was used and it was called 'sesba.' The subject had never heard of this food before and there was no reduction in the secretion during the first anticipatory period. On the second trial, however, the inhibition was pronounced. The organism had developed an inhibitory response to 'sesba' in one trial. If, on the other hand, the subject was informed that he would be given ice cream or apple or orange at the end of the two minute period there was invariably a slight increase in the secretion over the previous control period.

Discussion

Because of the possibility of the anticipation experiments accounting for the difficulties encountered in the other tests, we shall consider that data first. Expectation of disturbing experiences such as a shock or the ingestion of distasteful food caused a marked reduction in the quantity of secretion from the parotid glands. According to Pavlov (10) such a reduction is due to cortical inhibition. Cannon (3) attributes inhibition of the viscera during profound emotional states such as fear or rage to temporary domination of the sympathetic division of the autonomic nervous system. Under such organic states he has been able to show that all digestive processes are inhibited while stored adrenin and extra sugar are poured into the blood stream as it is shifted from the nutritive organs to the nerves and muscles. When, on the other hand, the organism is confronted by no such emergency as would

cause an emotion the cranial division of the autonomic has been shown to supply the innervation and regeneration becomes the chief bodily activity as reserves are piled up for growth and further emergency. Apparently these two neural divisions operating reciprocally under opposed centers in the nervous system play an important rôle in organic adjustment. Just as orderly functioning of the musculature of the body depends upon reciprocal innervation of antagonistic muscles, so efficient activity of the organism as a whole appears to depend upon reciprocal innervation of these antagonistic divisions of the autonomic system. This arrangement expressing itself as it does in excitatory or inhibitory states of the nutritive functions must be considered in the interpretation of these data.

If profound emotional states are of such importance in determining the direction and intensity of neural impulses, it would seem justifiable to assume that milder emotional states such as appeared to characterize the subjects in the experiments reported might have a similar although less intense effect. If such an explanation is well founded most of the difficulties encountered in attempts to condition the salivary glands in human subjects may be accounted for. An unfavorable mood or emotional tone on the part of the subject would cause the domination of the sympathetic system and positive conditioned responses could not develop. Certainly it is reasonable to assume that in most clinical or laboratory situations the attitude of the subject would be unfavorable to cranial functioning except under intense hunger. Pavlov has shown that when this nerve supply is severed in dogs, it is impossible to develop positive conditioned responses.

According to this interpretation the definite inhibition shown when the boy was working on the puzzles or doing the arithmetic would be accounted for in terms of his consuming interest or attention. It was made clear during the experiments that the inhibition disappeared when the puzzle was solved and appeared to be released gradually as the subject's interest in the problem solving waned.

Again our failure to condition an adult in an artificial eating situation while we were able to see evidences of a natural

conditioned response when the eating situation had become habitual, seems to be in accord with this explanation. The presence or absence of a favorable affective state appears to be crucial in conditioning salivary responses in man.

The affective state, on the other hand, might readily become conditioned just as an emotional response has been shown to become conditioned quickly. It has occurred to us that it is the affective state of the organism that is conditioned in all conditioned salivary responses. It is the sympathetic system or the cranial system as a whole that is conditioned rather than the specialized aspect of one component of the system. Evidence for such a belief is abundant but must be considered in a paper by itself.

The implication of our interpretation to learning is clear. If a mild emotional tone causes inhibition of nutritional activity thus releasing an additional blood supply to the nerves and muscles, and if this blood supply carries important chemicals which apparently are helpful in organic adjustment, it would seem that the known advantage of a favorable attitude in learning could be accounted for. A hopeful attack is thus suggested for a study of the influences on learning of such factors as attitude and attention. A study now in progress on the influence of attention parotid secretion is yielding some significant results.

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READING AND LEGIBILITY OF CHINESE CHARACTERS: III JUDGING THE POSITIONS OF CHINESE CHARACTERS BY AMERICAN SUBJECTS

BY SIEGEN K. CHOU[1]

As I have shown in my former two reports, *character-position* is the most detrimental factor influencing the speed of reading whole-characters and the speed of reading half-characters for reproducing the whole, among all the factors of *reading-direction, temporal-spatial sequence, character-position, character-exposure, and shutter-and-line-exposure.* For Chinese subjects who have been accustomed to the characters, the position of characters naturally exerts such an influence above all others. It may be questioned, however, whether it would disturb foreigners to the same degree who have no knowledge at all of the language; although I find that not infrequently an illustration, an advertisement, or a notice consisting of a number of Chinese characters is printed or placed upside-down in some journal, magazine, or Sunday paper. In view of the fact that, although the characters are squares and hence can be taken in any position, the arrangement, the nature, and the heaviness of the different strokes, *i.e.* the character-*Gestalt*, can hardly betray the correct position of the total character. It is the purpose of the following two experiments on American subjects to determine whether there is any such intrinsic quality in a character that determines the position or uprightness of it. This problem is an aspect of legibility inasmuch as legibility is primarily an attribute of the individual characters.

Experiment I: Individual Bradyscopic Test

Speed and Accuracy of Judgment through Simultaneous Voluntary Maintenance of Exposure.—For determining the

[1] The writer is greatly indebted to Professor Walter R. Miles for general supervision and constant encouragement. Thanks are due to the 149 subjects who took the tests. This paper is the third of a series on reading and legibility of Chinese characters. The first two appeared in this Journal, 1929, 12, 156–177; and 1930 13, 332–351.

approximate relative difficulty of the different positions of a character for their correct judgments by American subjects, I carried out one experiment early in 1928 at Stanford Univer-

FIG. I. Chinese characters in four positions to be judged singly by American subjects through *simultaneous voluntary maintenance of exposure* with the Quadrant Tachistoscope or Bradyscope. The actual size of the characters used is No. 1, about 14 mm square. The order of exposure of the 64 characters is from upper left ones rightward within the row and downward from row to row toward lower right ones. Compare Table I.

sity through *simultaneous voluntary maintenance of exposure* with the Quadrant Tachistoscope or Bradyscope[1] on seven American subjects.

[1] S. K. Chou, Reaction-keys and a new technique for reading-reactions, *Amer. J. Psychol.*, 1929, 41, 469–473. *Cf.* Tachistoscope vs. Bradyscope, *ibid.*, 1930, 42, 303–306. A quadrant tachistoscope for studying the legibility of Chinese characters, this JOURNAL, 1929, 12, 178–186.

The *materials* (Fig. I) used consist of 64 big size characters, ¼ of which are upright, ¼ upside down, ¼ turned to the right, and ¼ turned to the left. These characters were cut

TABLE I

SPEED AND ACCURACY IN JUDGING THE POSITIONS OF CHINESE CHARACTERS BY AMERICAN SUBJECTS

1 *u* *217* 6−1*r*	2 *d* *199* 6−1*r*	3 *r* *222* 4−3*l*	4 *l* *321* 4−2*r*, 1*l*	5 *l* *236* 6−1*r*	6 *r* *301* 4−2*l*, 1*u*	7 *d* *270* 5−2*u*	8 *u* *181* 7−
9 *d* *268* 4−3*d*	10 *u* *343* 4−3*d*	11 *r* *322* 4−2*r*, 1*l*	12 *l* *280* 4−3*r*	13 *l* *354* 6−1*r*	14 *u* *225* 5−1*d*, 1*r*	15 *d* *232* 3−2*u*, 1*r*, 1*l*	16 *r* *227* 4−2*l*, 1*u*
17 *u* *243* 4−3*d*	18 *r* *343* 4−2*u*, 1*d*	19 *l* *263* 5−2*r*	20 *d* *395* 6−1*u*	21 *d* *412* 4−3*r*	22 *u* *543* 5−2*d*	23 *r* *332* 4−2*l*, 1*d*	24 *l* *271* 5−1*u*, 1*d*
25 *u* *373* 4−2*d*, 1*l*	26 *d* *473* 5−2*d*	27 *l* *230* 4−2*d*, 1*u*	28 *r* *343* 4−3*l*	29 *l* *337* 5−2*r*	30 *d* *243* 3−3*u*, 1*l*	31 *u* *178* 7−	32 *r* *283* 3−3*l*, 1*d*
33 *l* *199* 5−2*r*	34 *u* *296* 6−2*d*	35 *d* *315* 4−2*l*, 1*r*	36 *r* *306* 5−2*l*	37 *d* *187* 4−3*d*	38 *l* *162* 4−3*r*	39 *r* *425* 4−2*u*, 1*l*	40 *u* *301* 4−2*d*, 1*l*
41 *r* *262* 5−2*l*	42 *d* *283* 6−1*l*	43 *u* *284* 7−	44 *l* *282* 4−2*r*, 1*u*	45 *d* *173* 5−2*u*	46 *l* *229* 5−2*r*	47 *r* *289* 4−2*l*, 1*u*	48 *u* *214* 6−1*d*
49 *l* *249* 4−3*r*	50 *u* *256* 4−3*d*	51 *d* *199* 4−3*u*	52 *r* *281* 4−3*l*	53 *u* *210* 5−2*d*	54 *d* *428* 3−2*r*, 2*l*	55 *l* *304* 3−2*r*, 1*u*, 1*d*	66 *r* *328* 4−2*l*, 1*d*
57 *d* *256* 5−2*u*	58 *u* *188* 6−1*d*	59 *r* *284* 6−1*l*	60 *l* *351* 5−2*r*	61 *d* *232* 6−1*u*	62 *u* *346* 5−2*d*	63 *r* *399* 3−4*l*	64 *l* *209* 5−2*r*

Table I corresponds to Fig. I. It reads, *e.g.*, character No. 1 is upright (*u*) and was judged by **6** Os correctly and by 1 to be turned-to-the-right (1*r*), taking a mean time of *217* (× .02) sec.

out from a specially printed sheet and were pasted on the regular stiff cards for exposing in the bradyscope. The serial

order of exposure of the different characters is marked by numbers in Table I facing Fig. I. Every position is used every four exposures but the sequence of the 4 positions is in chance order. The following *instructions* were read to each subject.

"Look attentively at the cross of the window in the hood and at the same time keep your right index finger barely touching the key. At the signal "Ready, go!," press the key down hard and hold it there. This will immediately open the window exposing a Chinese character. This Chinese character may be upright, it may be upside-down, it may be turned 90 degrees to the right, or it may be turned 90 degrees to the left. While you are holding the window open, study the character closely but quickly so as to determine its position, *i.e.* whether it is upright, upside-down, turned 90 degrees to the right, or turned 90 degrees to the left. As soon as you have determined upon the position of the character, respond as quickly as you can by saying 'upright,' if it is upright, 'down,' if it is upside-down, 'right,' if it is turned 90 degrees to the right, or 'left,' if it is turned 90 degrees to the left. Immediately *after* the verbal response, quickly release the key. Never release the key while you are studying the character as the releasing will immediately close the window. There are altogether 64 characters to be studied. The first 2 exposures are some English material for you to read silently in order to adjust yourself to the noise of the opening and closing of the shutter window. I will mark by a stop-watch in 1/50th of a second the time you take in studying the actual Chinese character in each exposure."

Accuracy in terms of number of correct judgments of the position of each of the 64 characters is shown in Table II together with the individual differences. The character-position symbols with a 'prime' mark mean the corresponding judgments.

Subject 5M made only 2 mistakes while 6D made 47 mistakes and had only 17 judgments correct. Out of the total 448 judgments, 290 are correct and 158 incorrect. The nature of the correct and incorrect judgments can be made out from the main columns of the table. Upright characters (u) are judged 84 times upright (u'), 24 times upside-down (d'), and 2 times each turned-to-the-right (r') and left (l'). Characters turned to the right are the most difficult to judge since the correct judgments are only 64 (rr') (Table II).

Upright judgments are the most frequent and mostly correct. Upside-down judgments have more correct ones than turned-to-the-right judgments although they are the least frequent (Table II).

Speed in .02 sec. is similarly shown in Table III. In order to weight out the individual speed factor so as to determine

more adequately, the relative difficulty of the different characters, the separate speed of every subject for every character is multiplied by a personal speed factor, which is the number

TABLE II

JUDGMENTS OF THE POSITIONS OF CHINESE CHARACTERS BY AMERICAN SUBJECTS

Accuracy

Char'er Posi'ns	Os	Judgments				Total		
		u'	*d'*	*r'*	*l'*	False	True	Os
u	1*R*	16	—	—	—			
	2*M*	10	6	—	—			
	3*R*	5	10	—	1			
	4*I*	16	—	—	—			
	5*M*	16	—	—	—	2	62	5*M*
	6*D*	7	6	2	1			
	7*L*	14	2	—	—			
		84	24	2	2			
d	1*R*	2	13	1	—	7	57	1*R*
	2*M*	7	5	3	1			
	3*R*	7	5	1	3			
	4*I*	2	14	—	—	8	56	4*I*
	5*M*	2	14	—	—			
	6*D*	7	6	2	1			
	7*L*	3	11	1	1	14	50	7*L*
		30	68	8	6			
r	1*R*	1	—	14	1			
	2*M*	2	1	5	8	33	31	2*M*
	3*R*	3	2	4	7	47	17	3*R*
	4*I*	1	—	13	2			
	5*M*	—	—	16	—			
	6*D*	3	1	2	10	47	17	6*D*
	7*L*	1	—	10	5			
		11	4	64	33			
l	1*R*	—	1	1	14			
	2*M*	—	1	4	11			
	3*R*	—	2	11	3			
	4*I*	—	—	3	13			
	5*M*	—	—	—	16			
	6*D*	5	—	9	2			
	7*L*	—	—	1	15			
		5	4	29	74	.....	.....	...
Total..		46 84 *130*	32 68 *100*	39 64 *103*	41 74 *115*	158	290 *448*	

Character-positions

Character-positions: *u* = upright; *d* = upside-down; *r* = turned to the right; *l* = turned to the left. Corresponding judgments: *u'*, *d'*, *r'*, *l'*. Figures in heavy broad face are numbers of correct or true judgments; ordinary figures are numbers of false judgments. Correct judgments of all 7 Os for each position of characters are totalled on the *right* side of the numbers, while false judgments are totalled on the *left* side. The *italics* are grand totals. The total correct and false judgments (all positions) of all 7 Os are summarized on the extreme right of the table.

of times his mean speed is shorter than the mean of the slowest person. Subject 5M's true mean speed for all judgments is 49 but his weighted mean speed for correct judgments is 301, *i.e.* if he were 6.10 times as slow as the slowest. Similarly, 4M's judgments take on the average 283, the slowest among the 7 subjects, but his weighted mean for correct judgments is 276, his speed factor being 1.00.

Turned-to-the-right judgments (*r'*) are the slowest to make as a whole, while upright judgments (*u'*) are the quickest to make. Judging characters turned-to-the-left as such (*ll'*) takes the shortest time, while judging those turned-to-the-right as such (*rr'*) takes the longest time. Generally speaking, correct judgments are made in shorter time than incorrect ones.

The Nature of Judgments of the Positions of Chinese Characters.—All judgments are either correct or incorrect. But the incorrect ones are of 3 different kinds. When a character turned-to-the-right is judged to be turned-to-the-left or vice versa and when an upright character is judged to be upside-down or vice versa, these incorrect judgments are of *opposite* nature spatially along the horizontal and vertical axes and conceptually about a central idea of lineal extension. When an upright character is judged to be turned-to-the-right or vice versa and when an upside-down character is judged to be turned-to-the-left or vice versa, these incorrect judgments are *analogous* in the sense that 'upright' and 'right' are primary or dominant while 'upside-down' and 'left' are secondary or inferior. When upright characters are judged to be turned-to-the-left or vice versa and when upside-down characters are judged to be turned-to-the-right or vice versa, these incorrect judgments are *crossed* just because they are not analogous in the former sense. Correct judgments are nothing but *identical* judgments: upright to be upright, upside-down to be upside-down, and so forth.

It has been shown that correct judgments are more frequent than incorrect ones for any true position of the character. This is what might be expected. But what is the relative frequency of these three classes of incorrect judg-

ments? Are there any significant differences among them both in accuracy and in speed?

TABLE III

JUDGMENTS OF THE POSITIONS OF CHINESE CHARACTERS BY AMERICAN SUBJECTS

Speed

udrl	Os	Judgments								Mean			
		u'		*d'*		*r'*		*l'*		False	True	Real	Os
u	1*R*	**269**		—		—		—					
	2*M*	**212**		283		—		—					
	3*R*	**246**		310		—		281					
	4*I*	**266**	**273**	—	332	—	189	—	257				
	5*M*	**296**		—		—		—		326	**301**	*49*	5*M*
	6*D*	**225**		362		188		232					
	7*L*	**335**		505		—		—					
d	1*R*	264		**247**		935		—					
	2*M*	196		**274**		412		508		304	**261**	*111*	2*M*
	3*R*	233		**315**		496		244					
	4*I*	663	**273**	**277**	**273**	—	443	—	320				
	5*M*	326		**292**		—		—					
	6*D*	229		**153**		317		427					
	7*L*	243		**318**		246		254					
r	1*R*	210		—		**299**		452		438	**267**	*125*	1*R*
	2*M*	459		437		**336**		321					
	3*R*	356		376		**258**		269		287	**287**	*133*	3*R*
	4*I*	90	300	—	414	**301**	**301**	198	317				
	5*M*	—		—		**339**		—					
	6*D*	261		264		**308**		349		305	**225**	*203*	6*D*
	7*L*	236		—		**244**		336		318	**269**	*222*	7*L*
l	1*R*	—		479		461		**251**					
	2*M*	—		272		259		**291**					
	3*R*	—		274		272		**341**					
	4*I*	—	271	—	325	295	294	**260**	**254**	337	**276**	*283*	4*M*
	5*M*	—		—		—		**275**					
	6*D*	271		—		315		**358**					
	7*L*	—		—		301		**187**					
Mean . .		**272**	**273**	**341**	**273**	**319**	**301**	**314**	**254**	**309**	**274**		
		273		*295*		*308*		*275*		*286*			

Character-positions

Character-positions: *u* = upright; *d* = upside-down; *r* = turned to the right; *l* = turned to the left. Corresponding judgments: *u'*, *d'*, *r'*, *l'*. Figures in heavy broad face are judging times in .02 sec. of correct or true judgments; ordinary figures are judging times of false judgments. Judging times of correct judgments of all 7 Os for each position are averaged on the *right* side of them, while judging times of false judgments are averaged on the *left* side. The *italics* are grand means. The individual records of all 7 Os are summarized on the extreme right of the table.

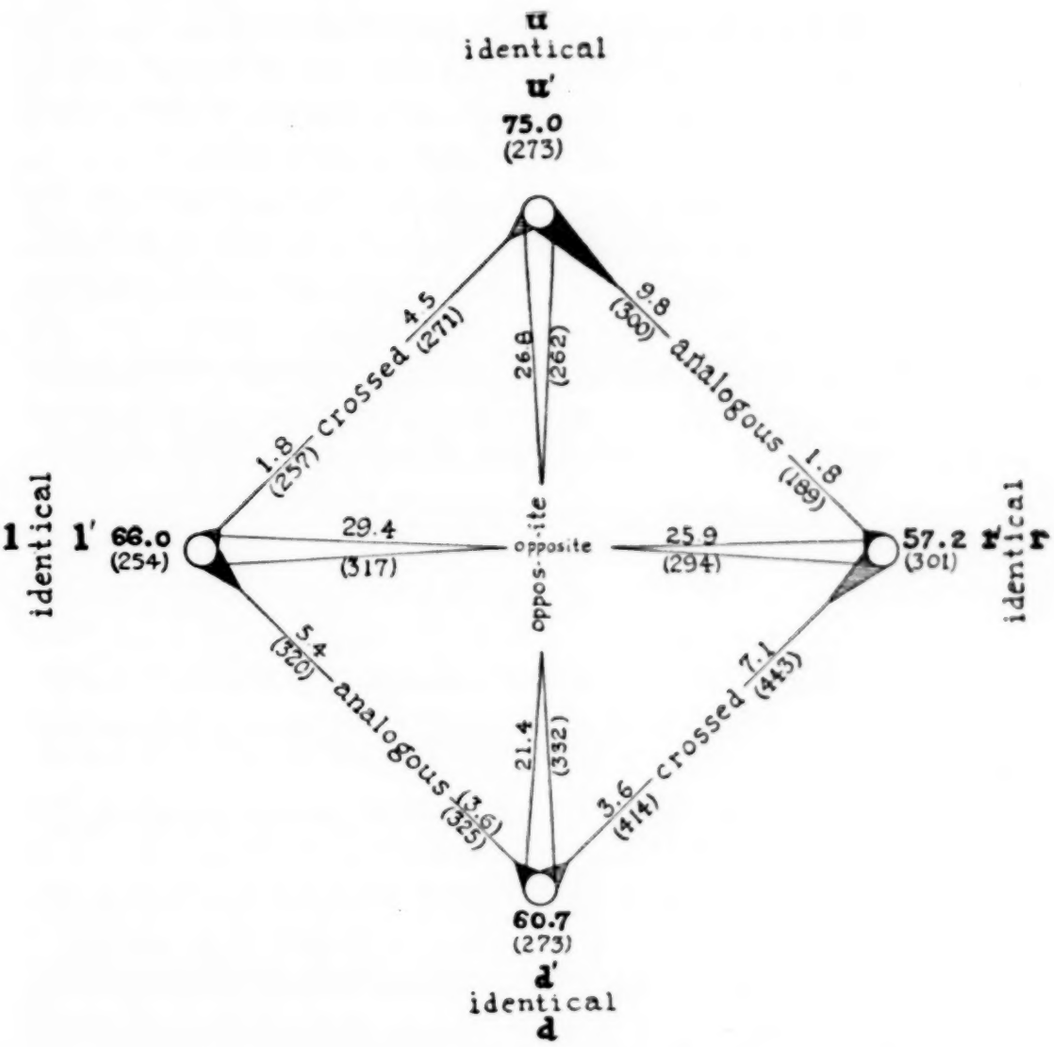

FIG. II. Speed and accuracy of judging the positions of Chinese characters by American subjects through *simultaneous voluntary maintenance of exposure* with the Quadrant Tahistoscope. The four circles represent both the true and the judged positions of a character. This is also denoted by the symbols, *u*, *d*, *r*, and *l*, and by *u'*, *d'*, *r'* and *l'* for the judged positions. The relative size of the solid and hollow triangles (representing different kinds of incorrect judgments) denotes the relative proportion of the percentages of these judgments. The true position of all characters denoted by the circle at the *base* of a triangle is judged in the position denoted by the circle away from the *apex* of that triangle. Thus, upright (*u*) characters are judged as upside-down (*d'*) in 26.8 percent of the cases. These incorrect judgments are of the *opposite* nature. Figures in parentheses are judgment times in .02 sec.

TABLE IV

SUMMARY OF SPEED AND ACCURACY

Judgments	Crossed	Analogous	Opposite	Identical
Percent	4.2	5.1	25.9	64.8
Time in .02 sec	(346)	(300)	(300)	(274)

This question is schematically answered by Fig. II. The little circles represent both the true and the judged positions of a character and the triangles the percentages of judgments for that position. The speed is given in parentheses.

Upright as upright (*uu'*) constitute 75.0 percent of the total judgments for that particular position, left as left (*ll'*) 66.0 percent, upside-down as upside-down (*dd'*) 60.7 percent, and right as right (*rr'*) only 57.2 percent. These are the *identical, i.e.* correct judgments, yielding a mean of 64.8 percent (Table IV). The *opposite* incorrect judgments average 25.9 percent, while *analogous* and *crossed* incorrect judgments average only 5.1 percent and 4.2 percent respectively. Generally, the higher the percentage of judgments, the quicker they are made.

This analysis seems to confirm the fact that the inability of foreigners lies more in opposite judgments whenever they encounter the situation of determining the true position of a Chinese character.

The relative difficulty of the different characters in different positions for judgment can be seen from Table I. The italicized figures are speed records and the next line reads, for example, in character No. 1, "6 subjects judged it as upright," that is, correct, and 1 judged it as turned-to-the-right, which is incorrect. Characters No. 8, 31, 43, were judged correctly by all 7 subjects.

Experiment II: Group Character-position Test

The Group Test.—In order to find out some of the possible cues used and character-parts dominant in the judging of the position of a Chinese character by American subjects, I devised along with the above experiment also a special test (Fig. III) for this purpose. I went to the typesetting department of a Chinese daily in San Francisco (all the other materials used in former experiments were also typeset by myself and printed at the same place) and picked up at random fom the type shelf a few characters from each and every radical group. Altogether 312 different[1] characters were set and printed in

[1] One character was later found duplicated, line 2, character 22 and line 10, character 17. Only one subject noticed this.

13 rows of 24 each. One quarter of them are upright, one quarter upside-down, one quarter turned-to-the-right, and one quarter turned-to-the-left. The sequence of the different positions is entirely in chance order.

The test sheet is accompanied by an instruction sheet, telling the person to mark the position of every character by the letter T in its various positions, to give the approximate

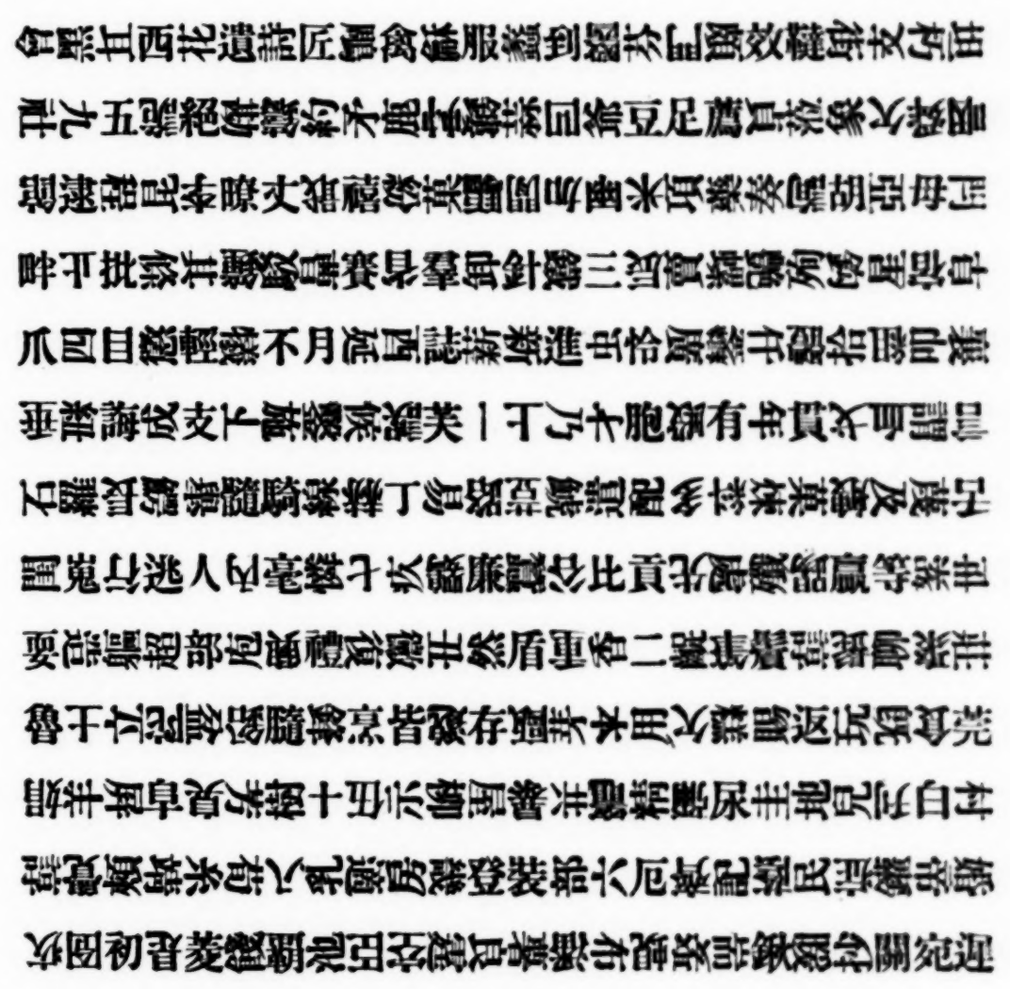

FIG. III. The Group Character-position Test Sheet

time for this marking, to indicate the degree of familiarity with the Chinese language, and, above all, to describe the bases or cues for judgment.

Data was collected on 110 students in introductory psychology at Stanford and Dr. Miles A. Tinker obtained 32 for me in the University of Minnesota. Both sexes were represented.

The distribution of the scores (number of characters whose positions are correctly marked) of all subjects is plotted in Fig. IV. There are 105 who marked every one of the charac-

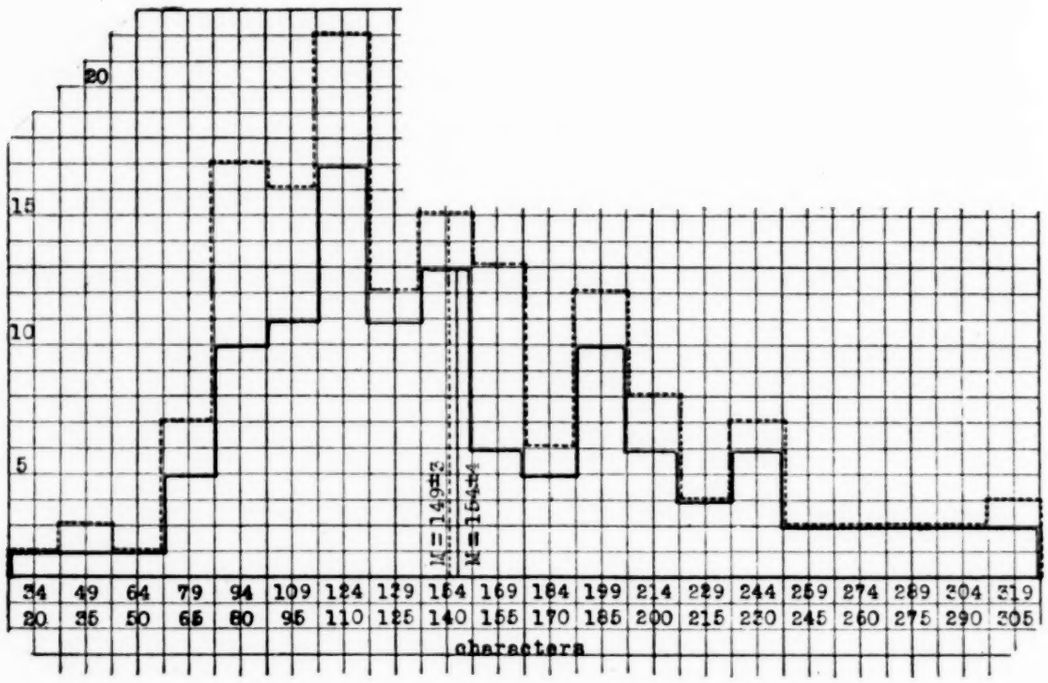

FIG. IV. Character-Positions: Number of Characters Correctly Marked
——— true score (N = 105)
– – – – true score and estimated true score (N = 142)

ters. These are plotted separately. The other 37 subjects missed willingly or carelessly a varying number of characters. Two marked less than a third of the total 312. The scores of all these persons were estimated by proportion from their actual true scores and plotted together with the rest.

The two distributions coincide fairly well. The mean for those who marked all of them is 5 characters higher than the whole group; these faithful markers correctly marked 154 characters while the average of the group is 149. This is less than half accuracy, whereas, in the former exposure experiment, out of a possible 448 judgments 290 were correct, more than half accuracy. More attention and seriousness in the controlled exposure experiment may account for this discrepancy. One Japanese made in the group test only two mistakes but one Chinese made 5, both marked all of them. One

American, who received a sample of a few characters for preliminary inspection and who discovered the only one duplicate character on the test sheet, made only 10 mistakes, while marking all. The lowest score from one subject was 31 although he did not omit any.

The mean time for those who did record their marking time is about 21 minutes. More took less than that (Fig. V).

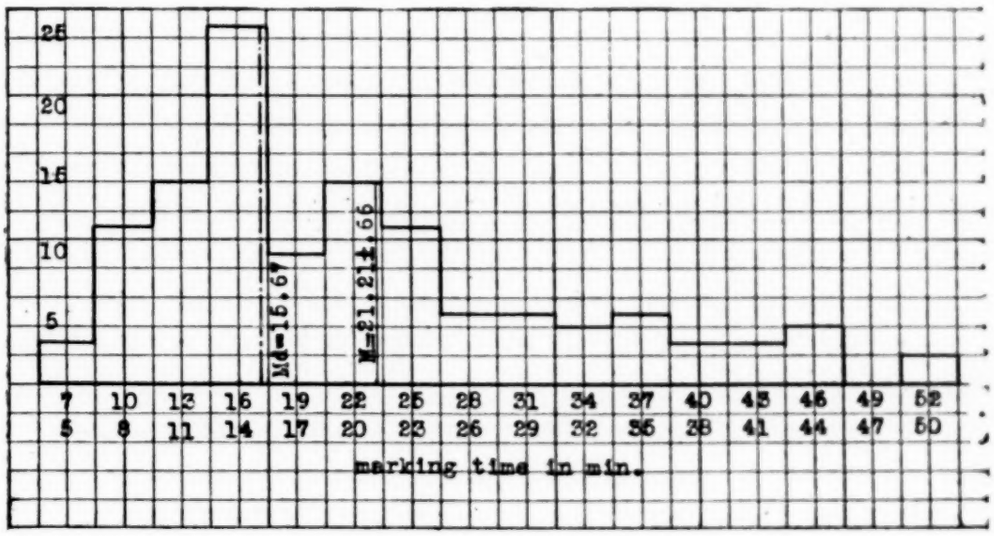

FIG. V. Time Taken for Marking the Characters (N = 118)

Cues Determining the Position of A Chinese Character.—It is certainly instructive and interesting to read the comments of 126 subjects who cared to write *something* after they took the test, 16 foregoing the privilege to say anything.

"It may be Chinese, but it's all Greek to me." "I have absolutely no basis for judging these characters." "Frankness is one of the human virtues. Lest I might otherwise hold myself lacking in it, I openly admit that my only reason for putting anything under the characters was that I had been asked to do so. Are criteria ever based on a complete absence of knowledge, I wonder?" So none of them made a score over 89, although all except one (who missed one) marked all characters.

But not all who got no cues made low scores. One marked 219 correct, perhaps because he has "seen numerous Chinese newspapers", although he confessed, "I have nothing what-

ever to base my decisions on except sight . . . but know nothing of the language, and so have based my decisions on the sense of sight." Another questioned, "Is it possible to find out how we rate?" But she marked 193 of them correct, still far above the average.

On the other hand, those who had cues did not necessarily make high scores. No fewer than a dozen worked on an entirely wrong assumption. The one who, marking all, made a score of 31 had only one cue and that was just the reverse of correct. The most important correct cue is that *all horizontal lines have a little bump on the upper end of the stroke.* He and two others took this to be at the lower left end and hence the absurdity. This most important cue has been taken also as turned to the right, *i.e.* it is upright when the line is vertical with the bump on the top. About 8 made this assumption. About 18 who discovered this as a cue took it in the right position.

Another obvious cue is that *all vertical lines are much heavier and all horizontal ones much lighter.* About 24 sensed this but there was one who took just the opposite hypothesis.

The base of the character is most frequently (about 46 times) used as a reference. It was assumed to be *broad, wide, open, straight, flat, even, long, heavy, dark, solid, light, small, and separated.*

The next most frequently used but not well defined criterion is *appearance*, which might mean any of these: *one-sided, natural, typical Chinese, emphasis, logical, being upright, best, looks right, feel, judgments, square, and Gestalt.*

The top of the character is not much less decisive of its position, although it was described only a little more concretely: *short, light, fine, sharp, square, pointed, broad, heavy, wide, open, and flat.*

It is only natural to find that *writing* was the next important cue. One based his judgments solely on this and commented, "Understand that Chinese characters are made with a brush and have determined position of character on the theory that each could be made easier from a certain position. The brush starting with a fine point and ending thick." However, this

is not universally true. The heaviness of strokes depends, besides, upon the direction of writing them. However, the printed characters are not quite amenable to *brush writing*. No wonder his score is less than average. Several characteristics were attributed to writing by a host of others: *tapered stroke, stroke direction, shaded at top of stroke, shaded at bottom of stroke, and curved down and out.*

Resemblance to or association with objects, English, and the very letter 'T' itself had been used quite a number of times as cues. A dozen or more claimed they did the marking simply *by guess or by chance*, although *balance or stability* was equally taken by others as a criterion. Only a few noticed *symmetry or proportion*; much fewer specifically made clear that they had some *knowledge.*

In an experiment on a group of 51 American subjects who were requested to compare the equivalent forms of the same passage printed in vertical and horizontal styles as to their relative legibility, Shen has ascertained [1] that the reasons given by those preferring the horizontal are very vague and indefinite, such as 'more natural', 'more easily seen,' 'less strain'; by those preferring the vertical, neat appearance, better spacing, more æsthetic appeal to the eye, ease in change of line, less fatigue, analogy to adding columns of figures, or 'more logical.' These are concerned, of course, with the characters in group, where every one of them are printed upright. These characteristics noted by Shen's subjects are, therefore, strictly speaking, not the intrinsic qualities of the individual upright characters but those of a number of *lines* of them.

Reliability and Other Correlations.—The reliability by correlating the scores of the odd versus the even numbered lines of 24 characters each is found to be .933 with a probable error of .011. Marking time and marking score are positively correlated only to the extent of .155 with a probable error of .061. This is not very significant.

There were 81 subjects from the Stanford group who happened to have available their grades in introductory psychol-

[1] E. Shen, An analysis of eye movement in the reading of Chinese, this JOURNAL' 1927, 10, 182.

ogy. The correlation between their psychology grade and their marking score is positive but even to a lesser extent of .107 with a probable error of .111, which is evidently not significant.

Summary.—Foreigners frequently confuse the true positions of Chinese characters. This suggests that Chinese characters have intrinsic qualities for legibility. Seven American subjects judged the true positions of 64 Chinese characters through *simultaneous voluntary maintenance of exposure* with the Quadrant Tachistoscope or Bradyscope. Incorrect judgments are of three kinds: *opposite*, as in taking an upright character to be upside-down; *analogous*, as in taking the same to be turned-to-the-right; and *crossed*, as in taking the same to be turned-to-the-left. These seven American subjects have about 65 percent accuracy in judging the true position of a Chinese character. When they make mistakes, the mistakes are mostly of the *opposite* nature. The time for judgment was also recorded. Generally, correct judgments are made in shorter time. A special group test was also devised to find out the main cues used by 142 American subjects in marking out the true positions of 312 Chinese characters specially printed on a test sheet. The characteristic differences between the horizontal and vertical lines are most suggestive of the true position of a Chinese character. This uprightness is inherent in every character. Chinese characters are good material for studies on perception.

(Manuscript received December 13, 1929)

THE RELATIVE LEGIBILITY OF MODERN AND OLD STYLE NUMERALS

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There are two styles of digits, either one of which may be employed in mathematical tables: (1) Old Style numerical figures which vary in height and vertical position (as 12345678 90), and (2) Modern Style digits, all of which are uniform in height and position (as 1234567890). Sometimes one and sometimes the other style is used in printing.

There are few facts concerning the legibility of digits. In the report (3) of the Committee on Type Faces it is recommended that modernized Old Style figures be used in mathematical tables. Milne (2) considers the old numerical symbols, in which most of the characters have heads or tails, to be more legible than those of uniform height. Tinker (5), in comparing the legibility of digits, letters and certain mathematical signs, demonstrated that the digits fall within the group of letters having fair legibility. Further experimental data are needed in this field.

In this experiment we have compared the legibility of Old Style numerals with that of Modern Style and ascertained the relative legibility of the separate digits in each style of printing. The experiment consists of two main parts. In the first part we determined, by the distance method, the realtive legibility of Old Style and Modern digits when read (1) in isolation, and (2) in groups. The speed and accuracy with which Modern and Old Style numbers in groups are read under normal reading conditions were measured in Part II.

Six students majoring in psychology served as subjects in Part I; twenty university sophomores in Part II. All subjects had emmetropic or adequately corrected vision.

Apparatus and Procedure

The apparatus for ascertaining legibility by the distance method (Part 1) consisted of an extended bench along which

moved a sliding carriage holding the digits to be read. One end of the bench was attached to a small table which carried a right-angled support with headrest attached. The stimulus material was uniformly illuminated with an intensity of 35 foot-candles per square foot. This apparatus is essentially the same as that used by Bentley (1) and Roethlein (4).

The isolated numerals, arranged in random sequence with each digit 4.5 cm from its nearest neighbor, were printed in five lines of four digits each on sheets of light cardboard 23 cm by 26 cm. Ten point type was employed for all printing in this experiment. There were ten and one-half sheets of Modern and an equal number of Old Style numerals, *i.e.*, each digit occurred 25 times.

The grouped numbers were printed on cardboard with five digits in each group. There were either 12 or 13 groups per sheet. With both styles of printing each number occurred five times at each position in the group. In all, each digit appeared 25 times in each style of printing. Care was taken to distribute practice and fatigue effects equally.

All observing was done in a semi-darkened room. After a short period for the observer to become adapted to the illumination of the room, a sheet of numerals was placed on the carriage, which was placed on the farther end of the bench, and readings began. Instructions were given to read the figures at a uniform rate of one per second, and to substitute "blank" for the name of any digit which could not be recognized. After the subject had read through the complete page of numerals the carriage was moved to a point twenty centimeters nearer his eyes. A second reading was made, and this procedure continued until every numeral on the sheet had been read accurately. The experimenter recorded on a duplicate sheet the misreadings (for numerals in isolation only) and the distance from the subject at which each digit was read correctly. Rest periods were allowed frequently.

Each sheet of numerals was read once by each of the six subjects, which yielded 150 readings of each digit in isolation and in groups for each style of printing.

Only group digits were made use of in Part II of the ex-

periment. Two sheets of Modern and two of Old Style numbers were prepared with 25 groups of digits on each sheet, each group of 5 figures being $2\frac{1}{2}$ cm from any neighboring group. The illustration of the room and of the stimulus material was the same as in Part I. The carriage with the reading copy was placed 20 inches from the observer's eyes. For 10 observers, the order of stimulus sheets was: (1) Modern type, (2) Old Style, (3) Old Style, (4) Modern, which was reversed with the remaining 10 observers. By means of a check sheet and stop watch the experimenter checked errors (for oral reading) and timed the readings. There were two sittings for each observer and at each sitting the series of 4 stimulus sheets was read through orally and silently. These subjects were instructed to work for speed and accuracy. An average of the two readings was taken as the score in each type of material.

Results and Discussion

Table I compares the relative legibility of the ten digits, and of Modern and Old Style numbers. The average of each digit is for 150 readings; the total averages for 1500 readings. The legibility score for any digit is represented by the average distance in cm from the eyes at which it was read correctly as shown in columns 2 and 4. The table reveals the order of legibility of numerals from most to least legible to be:

Modern (isolation): 7416903285,
Old Style (Isolation): 7460193528,
Modern (Groups): 7140298563,
Old Style (Groups): 8761940532.

The reliability with which the above rankings have been established was determined by correlating the results yeilded by 3 observers with the results of the other 3, and then applying Brown's "prophecy" formula $\left(r_x = \frac{N r}{1 + (N - 1) r} \right)$ to obtain the reliability of the results from all six observers. The reliability coefficients obtained follow:

Modern (Isolation), $r = .95$, $r_x = .97$,
Old Style (Isolation), $r = .96$, $r_x = .98$,
Modern (Groups), $r = .26$, $r_x = .41$,
Old Style (Groups), $r = .75$, $r_x = .85$.

The coefficients indicate that the rankings have been established with a high dergee of reliability for digits in isolation, and with fair reliability for Old Style numbers in groups.

TABLE I

LEGIBILITY OF THE NUMERALS: A COMPARISON OF THE RELATIVE LEGIBILITY OF THE TEN DIGITS, AND OF MODERN AND NEW STYLE NUMBERS

Digits in Isolation

Digit	Modern		Old Style	
	Average Distance in Cm	σ_{dis}	Average Distance in Cm	σ_{dis}
1	292.4	41.99	279.3	54.55
2	245.5	48.84	249.5	56.64
3	266.1	54.10	269.4	55.01
4	293.9	36.32	288.1	39.98
5	239.1	55.92	250.6	50.38
6	274.2	40.37	282.3	47.05
7	305.1	36.17	308.3	42.70
8	242.0	60.01	247.3	63.06
9	269.2	46.05	277.6	44.89
0	268.1	52.07	281.3	52.62
Av.....	269.4	53.72*	273.4	48.91*
		Digits in Groups		
1	254.3	54.75	252.7	56.30
2	214.0	56.23	207.6	56.26
3	189.6	59.85	210.7	70.03
4	244.1	46.32	243.5	46.46
5	199.4	59.26	216.5	60.77
6	195.1	57.80	253.5	59.77
7	258.9	51.59	255.3	53.60
8	211.5	68.85	255.9	56.29
9	212.3	61.98	245.5	55.13
0	223.2	54.65	233.5	57.39
Av.....	220.2	88.90*	237.4	60.51*

* These σ's are computed from the total averages, *i.e.* 269.4, etc.

The above rank orders for the relative legibility of digits in groups are probably not entirely valid. Roethlein (4) has pointed out that the legibility of a character within a group depends partly on the nature of the symbols on either side of it. These intercorrelations are discussed, therefore, with the above reservation in mind. Comparison of the rankings with each other yield the following correlations (rank-difference):

Modern (Isolation) vs. Old Style (Isolation), $\rho = .90 \pm .04$,
Modern (Groups) vs. Old Style (Groups), $\rho = .27 \pm .21$,
Old Style (Isolation) vs. Old Style (Groups), $\rho = .31 \pm .20$,
Modern (Isolation) vs. Modern (Groups), $\rho = .65 \pm .13$.

These coefficients signify (1) that with numbers in isolation the rankings for relative legibility are approximately the same for the two styles of printing, (2) that in groups the rankings correspond but little, (3) that small relationship exists in the rankings for Old Style numerals in isolation and in groups, and (4) that only a moderate correspondence is present between Modern Style digits when read in isolation and when read in groups. This seems to indicate that reading digits in groups, when compared with digits in isolation, is a situation that changes the relative legibility of Modern numbers only moderately, but changes the relative legibility of the Old Style numbers greatly. The variation in height and horizontal alignment in Old Style numerals is probably an important factor contributing to this change.

Examination of row 11 of Table I shows, for numbers in isolation, an average reading distance of 269.4 cm for all ten Modern Style digits and an average of 273.4 cm for Old Style digits. The ratio of D/σ_D is 2.10 which indicates that there are 98 chances in 100 that the difference between averages will be in the same direction in future experiments. In the last row of the table, for digits in groups, the averages are respectively 220.2 cm and 237.4 cm. The D/σ_D is 6.01 (99.999 chances in 100). These results suggest that for numbers in isolation, the Old Style are somewhat easier than the Modern to perceive, and that in groups, the Old Style are much more readable. The main differences between the two forms of digits are variations in height and horizontal alignment. This undoubtedly favored the Old Style numerals in the legibility test. Comparison of the 11th and last rows of the table reveal that numbers in isolation, for either style of printing, are always much easier to read than numbers in groups.

An analysis of the legibility of numbers in the initial and final positions in a group versus those within the group yielded the following averages:

Modern (Ends) Av. = 242.2 cm, σ_{dis} = 57.27,
Modern (Within) Av. = 205.4 cm, σ_{dis} = 102.50,
Old Style (Ends) Av. = 253.6 cm, σ_{dis} = 57.03,
Old Style (Within) Av. = 226.4 cm, σ_{dis} = 61.08.

The statistical significance of the differences between averages (ends vs. within group) for either style of printing is very certain. For Modern numbers, $D/\sigma_D = 8.97$; for Old Style, $D/\sigma_D = 8.88$. This agrees with Roethlein (4) who noted that letters at the end of a group are much more legible than those within the group.

The rankings yielded by the individual observers for legibility of digits in isolation corresponded fairly well with each other. The average intercorrelation for all six subjects was .62 ± .13 for Old Style, and .66 ± .13 for Modern numerals.

An analysis of errors, showing the kind and amount of confusions among digits, is given in Table II. The upper

TABLE II

CONFUSION OF DIGITS: SHOWING KIND AND AMOUNT OF CONFUSIONS

Modern Style Numbers

Digit	No. Times Read Wrong	Digits Confused with: Amount of that Confusion in Percent
1	185	3,24; 7,20; 4,16; 5,13; (27)*
2	362	7,22; 3,18; 5,15; 8,12; 9,10; (23)
3	307	5,22; 4,14; 2,13; 7,13; 9,13; 1,10; (15)
4	154	0,33; 6,27; 2,12; (28)
5	394	3,18; 6,17; 4,16; 8,13; 1,12; 9,10; (14)
6	270	4,34; 0,24; 8,14; (28)
7	99	1,36; 3,11; 4,11; 0,11; 9,10; (21)
8	364	6,21; 0,20; 4,18; 9,13; (28)
9	285	0,27; 6,17; 4,15; 8,12; (29)
0	252	6,31; 9,20; 8,16; 4,13; (20)
		Old Style Numbers
1	239	0,23; 2,21; 7,16; 4,13; (27)*
2	312	0,31; 4,18; 6,13; 3,10; (28)
3	305	5,25; 9,13; 7,12; 8,12; 4,11; (27)
4	196	6,25; 0,21; 2,16; (38)
5	372	3,25; 4,14; 6,14; 8,13; 7,10; (24)
6	253	4,28; 8,23; 0,15; 5,12; 9,10; (12)
7	87	1,24; 3,15; 2,12; 0,12; 5,10; (27)
8	350	6,25; 4,23; 9,15; 0,10; (27)
9	265	0,20; 6,19; 8,19; 4,11; (31)
0	167	2,30; 4,21; 6,20; (29)

* The numbers in parentheses indicate percentages of scattering errors.

half of the table which is concerned with modern numerals, fails to reveal any very consistent trend in type of mistakes. For the Old Style numbers in the lower part of the table, however, there is evidence of such a trend. A majority of the confusions occurred between digits of the same height (1,2,0), those which project above the line (6,8), those which descend below the line (3,4,5,7,9) or those with similar form (5,3;2,0). It is possible that a greater differentiation in form of numerals is advisable. The writer doubts, however, that many of the confusions given in Table II occur under normal reading conditions.

After observation on Part I of the experiment was completed the six subjects were tested for speed of reading Modern and Old Style numbers in groups using the procedure described for Part II (see above). Practically no difference in speed of reading was discovered between the two types of printing. Then 20 subjects with no laboratory experience with the numbers were tested with the following average results (time in sec. taken to read 250 digits):

Silent reading (Modern), Time = 55.5, σ_{dis} = 12.4,
Silent reading (Old Style), Time = 55.7, σ_{dis} = 13.0,
Oral reading (Modern), Time = 71.8, σ_{dis} = 11.6,
Oral reading (Old Style), Time = 70.7, σ_{dis} = 11.0,
Oral reading (Modern), Errors = 3.1, σ_{dis} = 1.9,
Oral reading (Old Style), Errors = 2.8, σ_{dis} = 2.1.

Comparing averages of Modern with Old Style, the D/σ_D for time on silent reading is .042; for time on Oral reading, .308; for errors on oral reading .476. Hence all of the differences are statistically insignificant. These results tend to show that, on the average, Modern numbers can be read under ordinary reading conditions just as fast and accurately as Old Style numbers.

The reliability of the above silent and oral reading scores was determined by correlating test with retest scores and applying Brown's "prophecy" formula. The reliability coefficients follow:

Silent reading (Modern), Time, $r = .92$, $r_x = .96$,
Silent reading (Old Style), Time, $r = .95$, $r_x = .97$,
Oral reading (Modern), Time, $r = .94$, $r_x = .96$,
Oral reading (Old Style), Time, $r = .95$, $r_x = .97$,
Oral reading (Modern), Errors, $r = .65$, $r_x = .79$,
Oral reading (Old Style), Errors, $r = .54$, $r_x = .70$.

These coefficients reveal that all the time scores have high reliability and that the error scores are reliable enough to justify group comparisons.

As demonstrated in Part I, Old Style are definitely more legible than Modern numerals. Apparently this difference in legibility is not pronounced enough to affect speed of reading or number of errors when the reading is done under ordinary reading conditions. It is very possible, when working with mathematical tables over comparitively long periods of time, that reading Modern numbers will fatigue the visual mechanism more than Old Style digits because of these legibility differences. If ease as well as efficiency (in terms of speed and accuracy) in reading is to be considered as a factor upon which the hygiene of a printed page depends, then Old Style rather than Modern numerals should be employed in mathematical tables and any other printed material where numbers in groups are used.

Summary and Conclusions

1. The relative legibility of Modern and Old Style numerals was obtained by determining the average distance from the eyes at which the numerals could be read correctly.

2. The speed and accuracy of reading the two types of numerals were also measured.

3. For digits in isolation the rankings for relative legibility with the two types of printing correspond very closely. There is little or no correspondence in rankings for the two styles of digits in the groups.

4. The rankings for relative legibility were established with a high degree of relaibility for digits in isolation.

5. Old Style were found to be somewhat more legible than Modern numerals when in isolation; much more legible when in groups.

6. The average coefficients of correlation between individual results (rankings for relative legibility) ranged from .62 to .66.

7. Errors, as represented by confusion of digits, were more consistent with Old Style than with Modern numerals.

8. Modern numerals were read, under ordinary reading conditions, just as fast and just as accurately as Old Style.

9. Because ease as well as speed and accuracy of reading should be considered in the hygiene of reading it is recommended that Old Style numerals be employed in any printing where digits are grouped in series.

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AN EXPERIMENTAL STUDY OF MEMORY AS INFLUENCED BY FEELING TONE

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The purpose of this study was to test experimentally the truth or falsity of the Freudian theory that we tend to forget the unpleasant more readily than the pleasant. Although considerable experimentation has already been done on this problem, the results to date have been both contradictory and inconclusive.

A careful analysis of the literature on the subject has led the writer to conclude that there are three essential requirements for a good test of memory in relation to feeling tone. (1) In order to make the test results meaningful, the total number of experiences from which the recalls are to be made must be controlled—otherwise it must be postulated that in life the pleasant and the unpleasant are equally present. To avoid this postulate, the percentages of pleasant and of unpleasant recalls should be substituted for the gross number of recalls. (2) The subjects themselves must determine the feeling tone of the experiences or stimuli involved. Although this point has not been greatly stressed heretofore, it appears to the writer to be of supreme importance, since what seems pleasant or unpleasant is a highly subjective matter, the same stimulus eliciting one response from one individual and the reverse from another. (3) The experience must have a considerable degree of "vitalness" to the subject; in other words, it must have a definitely affective tone.

Not all of these requirements have been met by the tests hitherto used in studying this problem. Indeed very few have fulfilled all three, and it is possible that the confusion in results may be partially explicable on this basis.

Most of the earlier experiments tended to neglect the first requirement entirely, the numerical equality of pleasant and

unpleasant experiences being quite generally assumed. This criticism applies particularly to the questionnaire studies of Colgrove (**1**), of Kowalewski (**8**) and of Henderson (**6**), and to the association tests of Peters (**12**) and of Griffitts (**5**). That this factor may be important is shown by the study of Wholgemuth (**17**) in which he first re-interprets the results of Kowalewski's diary experiment (**9**) and then repeats the experiment using percentage of pleasant and of unpleasant recalls in place of gross totals and getting quite different results from those of the original study.

The second essential, individual determination of feeling tone, is neglected in the controlled association tests of Tait (**15**) and of Tolman and Johnson (**16**).

Probable absence of the third essential, "vitalness" to the subject, may explain the lack of positive results in the odor experiments of Gordon (**4**) and of Henderson and Bolton (**7**); also in the memory-for-pictures experiment of Gordon (**3**) and the memorization-and-recall-of-sonnets experiment of Charles Fox (**2**), although in the last named study, ease of learning as well as affective tone may have helped to determine the recalls.

The personality-memory test of Laird (**10**), the word study of Meyers (**11**) and the recall-of-photographs experiment of A. R. Stone (**14**) come closest to fulfilling all three requirements, although no one of these was sufficiently well controlled.

If the results of an experiment are to be at all conclusive, there must also be adequate statistical treatment of the data, and this factor too has been rather generally neglected in previous studies of memory and feeling tone. In no case, for example, has the standard error of the difference been calculated, a very important point in view of the small populations represented in many of these experiments.

Methods and Subjects

The procedure in this investigation was to approach the problem from several angles by a series of six tests, of which four satisfy all three of the essential requirements outlined above, while in two only the second and third are satisfied.

The first group on which the tests were tried out was a low freshman high-school classs of 30 members.

Test 1. Recollections of early childhood. The subjects were asked to list all the experiences they could remember which had occurred prior to their beginning school, and to classify them as pleasant or unpleasant. This test will be seen to leave the first requirement unfulfilled.

Test 2. Grammar-school recollections. This test is identical with the one above, except that the period was confined to grammar-school days. It too failed to meet the first requirement.

Test 3. Diary records. For this part of the experiment each subject kept a diary for five days, recording each entry under the heading of pleasant or unpleasant. A first recall was made at the end of two weeks, and a second at the end of a month. In this test, the diary record itself gave the number of original experiences from which percentages of recalls could be calculated, thus satisfying the first requirement, and as the subjects classified all events as to feeling tone, the second essential was also controlled. Chance undoubtedly determined to a considerable extent how vital were the experiences listed, but as the diary was kept for five days it seems fairly safe to assume that some vital events were included, especially since this particular week was the one in which the quarterly grades were announced.

Test 4. Word lists. For the fourth test, each subject was asked to make a list of twenty words which had a very pleasant connotation for him and twenty a very unpleasant one. These were recalled at the end of a month. This test will be seen to meet satisfactorily all three requirements, and is probably the best controlled of all the tests used.

Test 5. Memory for poems. The subjects of the first group in the course of their regular class work in English were required to read in class 47 narrative poems, and to rate each one as pleasant or unpleasant according to the effect the poem made upon them. There is no reason to believe that the responses were other than sincere as the reason given for the rating was that the teacher wanted their assistance in selecting

material for the next year's class. A month later, after reviewing the poems for a test, the pupils were asked to write the titles of all the poems they could remember. This test is seen to fulfil fairly well all three of the requirements.

Temperament rating. The 30 members of the class, all of whom had spent at least one year in the same room, were then asked to rate each other on a five point scale for temperament as follows:

5 Very optimistic
4 Fairly optimistic
3 Neutral
2 Fairly pessimistic
1 Very pessimistic.

A pleasantness-unpleasantness ratio was then computed for each subject by dividing the sum of the pleasant recalls on the five tests by the sum of the unpleasant. This ratio was then correlated with the optimism-pessimism rating made by the class.

In order to try out the experiments on a larger population, three other teachers in the same school were persuaded to cooperate in the undertaking, and 100 pupils from the sophomore, junior and senior classes were included in the study.

Test 3. (*Diary records*) *and Test 4.* (*Word lists*), which are obviously the best controlled of the five tests previously described, were given the larger group. In this case the diary was kept for but one day.

Test 6. Current events test. An additional test was also given to the second group, in which each subject read a certain copy of a current events magazine and tabulated every piece of information which seemed to him either very pleasant or very unpleasant. This material was recalled at the end of a month. Though the requirement of "vitalness" is perhaps less well controlled here than in Test 4, this also meets the three requirements quite satisfactorily.

Procedure

In order to eliminate the test situation as fully as possible, all of the tests included in this experiment were given by the

regular teachers in connection with the usual class work. Tests for Group I were a part of the English work and for Group II of the English and history work, the current-events tests being particularly well adapted for administration in the latter class.

The experiment ran throughout a whole semester of eighteen weeks, as it seemed desirable to leave an interval of at least two weeks between tests. In Group I, Test 5 (Memory for poems) was given first, followed successively by Test 1 (Recollections of early childhood), Test 2 (Recollections of grammar school), Test 4 (Word lists) and Test 3 (Diary records). They were all given at the same hour of the day, from nine to ten o'clock in the morning.

The tests for Group II were given at the eight o'clock period in the following order: Test 3 (Diary records), Test 4 (Word lists) and Test 6 (Current-events test) with intervals of two weeks between.

Excellent cooperation was given by all the students taking part in the experiment, and few seemed to have any suspicion that the purpose was other than that of the ordinary class work. One senior did inquire whether there was "anything

Results

Data from the Six Tests of Memory in Relation to Feeling Tone

Test	N	Pleasant			Unpleasant			Difference		
		M	S.D.	σ_M	M	S.D.	σ_M	D_M	σ_{D_M}	$\frac{D}{\sigma_D}$
Group I										
1. Recollections of early childhood	28	6.43	3.36	.63	5.21	2.87	.54	1.22	.83	1.46
2. Recollections of grammar school	24	6.41	2.95	.60	3.96	2.44	.50	2.45	.78	3.14
3. Diary records (Five days)										
First recall	29	33.20	11.50	2.13	31.13	20.09	3.73	2.07	4.29	.48
Second recall	28	25.39	12.54	2.37	18.78	15.48	2.92	6.61	3.76	1.76
4. Word lists	27	37.92	14.59	2.81	23.55	10.84	2.08	14.37	3.50	4.10
5. Recall of titles of poems	27	56.44	13.49	2.60	31.62	16.66	3.20	24.82	4.12	6.02
Group II										
3. Diary records (One day)	101	32.05	18.36	1.75	16.21	14.80	1.41	15.84	2.25	7.04
4. Word lists	101	37.69	18.57	1.85	15.47	8.33	.83	22.22	2.03	10.95
5. Current events	104	20.86	13.16	1.29	13.50	10.66	1.04	7.36	1.66	4.43

psychological about this" but apparently the idea did not occur to any of the freshmen, nor indeed to any others so far as could be discovered.

Summary of Results

1. Although not all of the tests showed significant differences between the recall of the pleasant and the unpleasant, all the results point in the same direction—namely to the more ready recall of the pleasant.

2. Three of the tests given to Group I (Recollections of grammar school, Word lists, and Memory for poems) show a difference of three times the standard error.

3. The correlation between the optimism-pessimism rating of fellow pupils and the pleasantness-unpleasantness ratio of the sum of the test scores was found to be $-.02 \pm .15$, or purely a chance correlation. Accordingly, temperament, or at least temperament as judged by schoolmates, cannot explain the greater recall of the pleasant.

4. All the tests given to the larger group show a difference of considerably more than three times the standard error.

5. The tests which best fulfil the three essential requirements given at the outset show the greatest differences, the test considered best in this respect giving by far the most reliable results for both groups.

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A NEW TYPE OF LIP-KEY

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This lip-key[1] has several advantages over the older types, Jastrow's, Cattell's, Meumann's, or Muller and Pilzecker's.[2] It requires the subject to hold a minimum of material between his lips or teeth; merely the end of a strip of paper 1 in by 4 in. The paper is easily changed from one subject to another, so the apparatus is perfectly sanitary. No metal touches the mouth, so there is no danger that an electrical shock will punish the subject and destroy his cooperation in the experiment. The device automatically pulls the paper strip entirely free from the subject's mouth the moment he releases his hold, thus removing interference with free vocal expression. The electrical contacts are so arranged that the subject's reaction will either make or break a circuit.

A swinging arm of wood (*A*), 14 in long and 1½ in wide, is pivoted 2 in from one end upon a vertical steel rod (*R*) 3/8 in in diameter and 16 in long. The rod is fitted into a stand at its lower end where it is adjustable in height for the individual subject, by means of a set-screw (*C*). It extends 10 in below the wooden arm. About 3/4 in above the arm it is bent at right angles to project 2 in beyond the short end of the arm. The end of the rod is then bent down at right angles and it extends 3/4 in to the level of the arm.

A short spiral spring (*S*) is attached from the end of the rod to the short end of the arm. This spring allows the arm to be turned on its pivot to some extent, but when released the arm comes back to the point of least tension. A brass bushing (*B*), with a thin circular disk of the same material about 1 in in diam-

[1] The device was designed and constructed by Richards with minor suggestions from Guilford who is responsible for this written description.

[2] For a description of various types of lip-keys, see E. B. Titchener, *Experimental Psychology*, 1905, v. II, Pt. 1, pp. 165f.

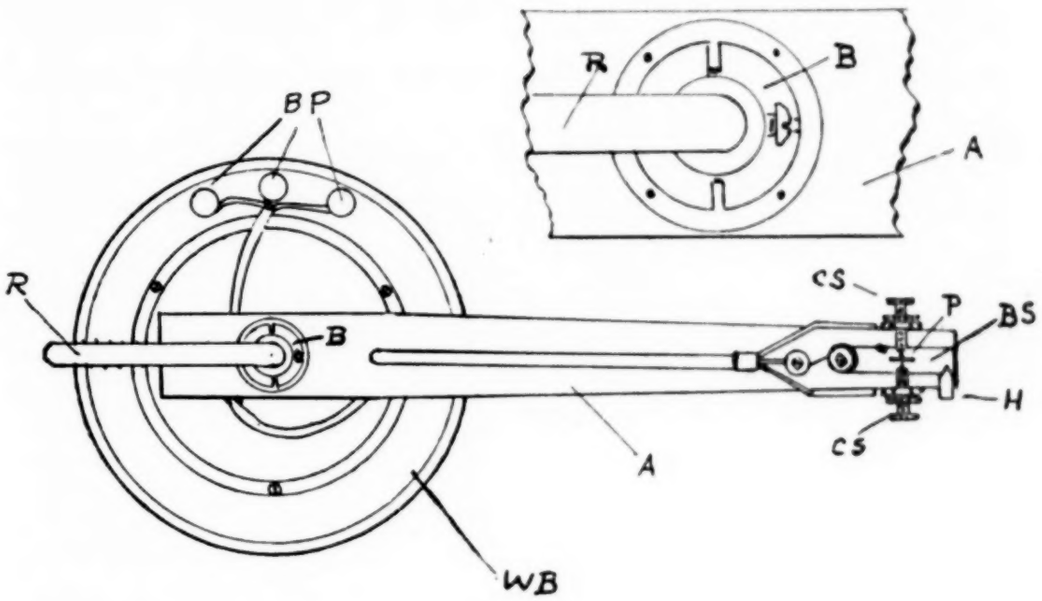
eter attached, is fastened to the rod just above the arm by means of a set-screw. The surface of this disk is in contact with a similar disk on the arm and the two furnish sufficient friction to make the action of the arm sluggish and to prevent any rebound when the spring has pulled the arm back and the paper away from the mouth of the subject. A spiral spring (*J*) is wound loosely around the rod just below the arm. This spring serves to control the amount of friction of the arm and it is adjustable by means of the metal collar and set-screw (*M*) on the rod at its lower end.

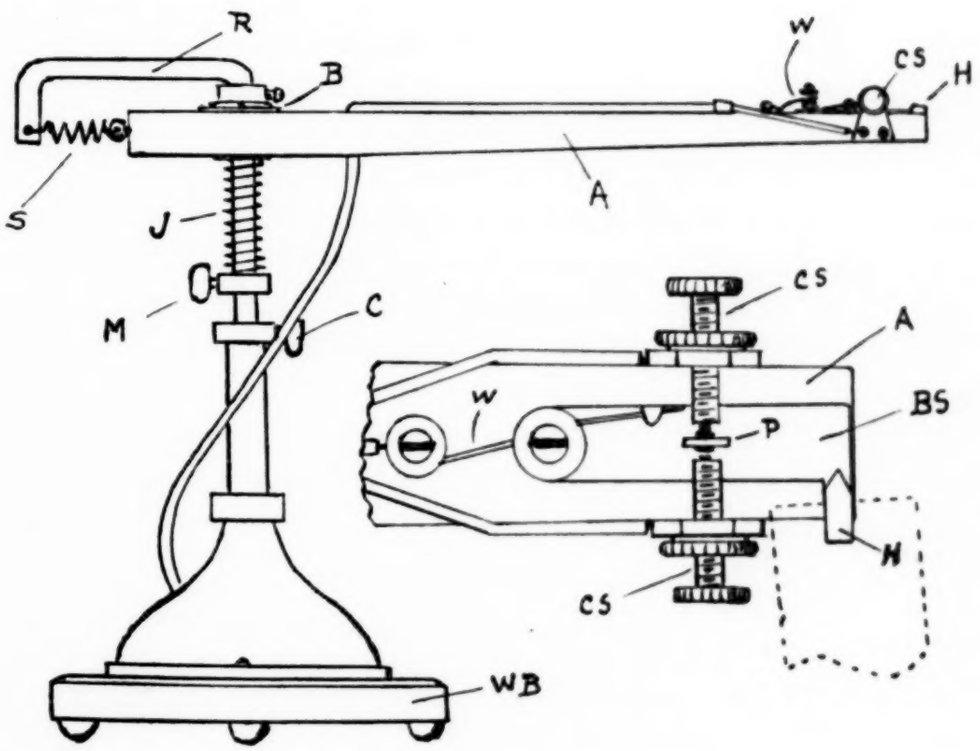
At the long end of the arm is a flat brass hook (*H*), 3/16 in wide, upon which to fasten the strip of paper which the subject seizes between his teeth. It is flat rather than round in order that the paper may not turn or tear so easily upon it. It is attached to a thin brass strip $2\frac{1}{4}$ by $\frac{1}{2}$ in (*BS*), which is pivoted at the opposite end and which has near its middle a small upright piece of brass sheeting (*P*) about 3/8 in tall by 1/4 in wide, tapering toward the top. This piece carries at its upper end a double contact-point of silver. The contact-point is separable by a small fraction of an inch fron two adjustable contact-screws (*CS*) on either side. These contact-screws are set into pieces of brass 3/4 in by 3/4 in by 1/16 in which are screwed to the sides of the wooden arm (*A*).

A stiff wire spring (*W*) is wound around a short post 3/8 in high, which stands at the pivot of the brass strip (*BS*). This spring holds the contact-point in touch with one of the contact-screws. When a strip of paper is placed upon the hook and held taut, the contact-point is removed from the one contact-screw and brought against the other. Thus a make or break can be brought about by releasing the paper. Three wires lead from the two contact-screws and from the thin brass strip (*BS*) to three respective binding-posts (*BP*) upon the wooden base (*WB*) upon which the whole instrument stands.

The operation of the device is simple. The subject attaches one end of a strip of paper to the hook, rotates the whole instrument upon the table until the free end of the paper is about 5 in from his lips, then he pulls the paper forward until

it can be grasped by his teeth. The instrument need not be clamped to the table, for three rubber pieces on the bottom of the wooden base prevent it from sliding. We find it better to hold the paper with the teeth than with the lips to prevent any possible sticking of the paper and hence a delayed release.





Pulling the paper forward puts both springs under tension; the spring (*W*) which controls the contact-point, and the spring (*S*) which controls the position of the arm. The moment the subject starts to utter a sound the paper is released. Spring (*W*), having practically no resistence left, causes the contact-point to swing over instantaneously. Spring (*S*), which is working against some friction, causes a relatively sluggish movement of the arm which pulls the paper away from the subject's mouth.

In order to test the reliability of the key for different words, we obtained a series of simple reaction times in which the stimulus was a sharp sound and the response was one of six words. The six words were chosen so as to give a wide variation in the initial sound. They were: core, data, wonder, sandy, Harry, and grand. Ten reactions were given with each word as the response, in the order in which we have just mentioned them, and then ten reactions with each word, taking them in the reverse order. The average reaction times in the first order were: 172.8, 143.7, 117.5, 100.2, 120.4, and 110.4, respectively. In the reversed order the average times were: 100.5, 100.5, 99.0, 100.6, 99.6, and 98.6, respectively. While it would seem from the results of the first series that there is a large variation in reaction time which is due to different initial sounds, there is such remarkable uniformity in the second series as to support our conclusion that the initial sound of the verbal response has no effect upon the reaction time with this type of key. The reduction in reaction time and the increase of uniformity as the experiments progressed are due to practice and to a more constant attitude. The average times are extremely short, especially in the second series. It may be that our subject is an exceptionally quick reactor, or it may be that this type of reaction is quicker than a finger-reaction; we do not know. At any rate, it indicates that there is no appreciable delay due to the working of the key itself.

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